An Atlas of Lithofacies of the McMurray Formation Athabasca Oil Sands Deposit, Northeastern Alberta: Surface and Subsurface

Earth Sciences Report 2000-07

Alberta Energy and Utilities Board

Alberta Geological Survey

AGS

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1.0 OVERVIEW

Detailed sedimentological and stratigraphic analysis of 45 outcrops, 140 cores and stratigraphic picks from over 4 000 well logs, along with preliminary palynological analysis, allow for a better understanding of the preserved stratigraphy and depositional settings of the Athabasca oil sands deposit, hosted primarily by the McMurray Formation, in northeastern Alberta. Facies analysis indicates that the Lower Cretaceous McMurray Formation was deposited and reworked as fluvial, estuarine and coastal plain sediments within an evolving landscape that changed from incised-valley fills carved on a regional unconformity, to broad estuaries, lakes and bays on a coastal plain. Locally, Devonian weathered limestone basement highs pierced the landscape. Sedimentation on top of bedrock highs was typically low, resulting in localized condensed sections. Elsewhere, within incised paleovalleys with high sedimentation rates, a more complete stratigraphic succession is preserved. The Lower Cretaceous McMurray Formation records a sedimentary history of repeated erosional and depositional cycles, resulting in significant unconformities at the base and top, and internal disconformities within the succession.

Former informal stratigraphic subdivisions for the McMurray Formation included the Lower, Middle and Upper McMurray (Carrigy, 1959). Other workers have subdivided the Wabiskaw/McMurray interval into ‘basal McMurray’ and ‘Wabiskaw/McMurray.’ During the present study detailed facies and biostratigraphic analyses of units formerly defined as Middle and Upper McMurray show no difference in age, and any facies variations appear to relate to paleogeographic controls. Additionally, units from what were originally called 'Middle' and 'Upper' appear to be a single, genetically-related and conformable succession with no regionally significant internal boundary or disconformity. By contrast units previously called ‘basal McMurray’ or ‘Lower McMurray’ are distinct lithologically, have different biostratigraphic ages, and are overlain unconformably by younger units of the McMurray succession. Thus it is recommended here that the informal term ‘Middle McMurray’ be abandoned, and what was formerly mapped as Middle McMurray now be included as part of the Upper McMurray. What was formerly designated as 'basal' or ‘lower’ McMurray is called Lower McMurray. In summary, it is proposed that the two mappable informal members of the McMurray Formation are the Lower McMurray and Upper McMurray, which are separated by a disconformity.

Units within the Lower McMurray, interpreted as part of a fluvial lowstand system, host rich bitumen- and water-sand reservoirs that accumulated as incised paleovalley-fills cut within the karstic pre-Cretaceous landscape. Lower McMurray bitumen reservoirs include braided channel-and-bar sands and intraclast mudstone breccias. Localized to laterally extensive water sands occur in paleolows along the basal pre-Cretaceous unconformity. The Upper McMurray succession, comprising estuarine and nearshore deposits of the overlying transgressive system, contains rich bitumen reservoirs, hosted within estuarine channel complexes that are often stacked above the Lower McMurray channel sands. Local water sands occur in the lower portions of the Upper McMurray succession, with somewhat isolated gas reservoirs in the upper parts of the succession, particularly along trend with the Prairie Salt Scarp. The uppermost part of the succession records the final stages of estuarine sedimentation that includes abandonment filling of late stage channeling, crevasse splays and tidal mud and sand flats associated with coastal plain sediments.

Although there is a high degree of heterogeneity within the McMurray Formation, much of this apparent heterogeneity can be simplified when a unified facies classification, as developed in the present study, is used. This type of classification affords comparison between different areas on a regional basis. The lithofacies scheme developed here will allow future detailed descriptions of various reservoirs, including regional mapping and characterization of various the water-, gas- and bitumen-resources of the McMurray Formation.

2.0 INTRODUCTION

The purpose of this study is to provide geological information important to in situ recovery and surface mining schemes, to assist in government planning and administration of the oil sand resource, and to help industry in the orderly development of the vast Athabasca deposit.

Reservoir properties are usually site specific; thus much of the previous work on the oil sands has been focussed on detailed geological studies in small areas. The objective of this project is to characterize the reservoir properties of the McMurray Formation within the Athabasca oil sands deposit on a regional scale. Two approaches are taken:

First, to classify the McMurray succession into different lithofacies and lithofacies associations. To complete the facies analysis, detailed studies were conducted in areas containing dense data coverage including outcrops (cf. Cotterill *et al.*, 2000), closely spaced wells and, less commonly, high resolution seismic (cf. Langenberg *et al.*, 1999). By default, these areas often were located in the surface mineable area of the Athabasca deposit.

Second the empirical results from the first phase will be used to broadly characterize the entire study area with formation picks, digital well logs, and core analysis data. This second and more regional approach, currently underway, will have direct application to exploration and in situ development of the Athabasca oil sands deposit.

2.1 Previous Work

An historical overview of the discovery and development of the Athabasca Oil Sands is given in Carrigy and Kramers (1973), with highlights from their compilation reprinted in Wightman and Pemberton (1992). The first descriptions of the Athabasca oil sands were given during reconnaissance mapping by the Geological Survey of Canada (Bell, 1884; McConnell, 1893). A formal definition of the McMurray Formation was given by McLearn (1917), with assessments of the extent of the oil sands and potential for commercial operations done by Federal Government surveys from 1926 to 1949 (Ells, 1926; Government of Canada, 1949; Hume, 1947, 1949). A lifetime of work on the stratigraphy, sedimentology and geology of the oil sands was done by Carrigy (1959a, b; 1962; 1963a, b; 1966, 1967, 1971) who, in 1959, designated an outcrop type section for the McMurray Formation along the Athabasca River (Carrigy, 1959a). Other studies include petrologic/mineralogic research (Mellon, 1955, 1956), statistical analysis of grain size distributions (Zwicky, 1979), biostratigraphic dating and palynological work (Mellon and Wall, 1956; Singh, 1964; Vagvolgyi and Hills, 1969; Burden, 1984; Wightman et al., 1987).

A number of field guides have been written about the geology of the Fort McMurray area, with emphasis on the oil sands (Carrigy, 1959a; Carrigy and Kramers, 1973; Kramers, 1973; Mossop *et al.*, 1982; Stewart and MacCallum, 1978; Wightman and Pemberton, 1992, 1993). An update of a field guide to the oil sands of the Fort McMurray area is presently being prepared, that incorporates the lithofacies scheme presented here (Cotterill *et al.*, 2000).

Application of outcrop analogues to detailed reservoir characterization has been done by Strobl *et al.* (1991, 1997a, b), with direct application to oil sand deposits at the AOSTRA Underground Test Facility (presently referred to as the Dover River Project, operated by Northstar Energy Ltd.). Otherwise there has been little direct application of outcrop exposures to either the in situ subsurface areas or the surface mineable areas, except in local areas. Cuddy and Muwais (1987) mapped channel-fills in the McMurray succession and used these to aid in assess their impact in the surface mineable area. Flach (1977, 1984), working in the Steepbank River area, found a difference between facies preserved in outcrop versus those encountered in core from nearby wells. O'Donnell and Jodrey (1985) and Wightman and Pemberton (1993) synthesized outcrop data and mine-site data to aid in sampling and prediction of bitumen-pay in surface mineable areas.

In the 1970s and mid 1980s studies focussed on facies analysis and paleogeographic reconstructions on oil sands at selected outcrops or cores (Flach, 1977; Flach, 1984; Flach and Mossop, 1985; James, 1977, 1985; James and Oliver, 1978; Mossop, 1978, 1980a,b; Mossop and Flach, 1983; Muwais and Smith, 1990; Muwais and Strobl, 1991; Smith, 1987, 1988a, b). In the mid 1990s the Alberta Geological Survey has taken a more regional approach, using a sequence stratigraphic framework and integration of earlier work into an Athabasca Oil Sands Database, at a scale of resolution of 4 wells per township (Wynne *et al.*, 1994). In doing these regional studies workers at the Alberta Geological Survey divided the Athabasca deposit into four regions for reservoir characterization, specifically Athabasca North, Athabasca South, Athabasca West, and Athabasca Central. More regional paleogeographic interpretations are given by Williams (1963) and Cant and Abrahamson (1996) for the Mannville Group; by Keith *et al.* (1988, 1990) and MacGillivray *et al.* (1988) for Athabasca Central; by MacGillivray *et al.* (1992) for Athabasca South; and, by Strobl *et al.* (1993, 1997a, b) and Wightman *et al.* (1997) for Athabasca West regions. Ichnological and sequence stratigraphic work was conducted by Pemberton and coworkers mainly for Athabasca South and North regions (Mattison and Pemberton, 1989; Mattison *et al.*, 1989; McPhee and Pemberton, 1994; Pemberton *et al.*, 1982; Ranger, 1994; Ranger and Pemberton, 1988, 1997; Ranger *et al.*, 1988). Most recently McPhee and Ranger (1998) presented a discussion of the distribution and regional geology of the oil sands and heavy oil deposits of western Canada, with applications of a sequence stratigraphic approach to petroleum geology. A synthesis report was compiled for the four regions outlining a stratigraphic analysis for the entire Athabasca deposit (Wightman *et al.*, 1995).

The present work at the Alberta Geological Survey dealing with facies classification of the oil sands is part of a larger three-year project that began in 1997 as reservoir characterization of the oil sands in the Athabasca deposit. A progress report for the first year of the study, 1997-98 (Berezniuk *et al.*, 1997) focused on:

- previous work and background;
- an assessment of in situ technologies and their relation to reservoir characterization;
- identification of areas for detailed characterization of reservoir geology; and,
- the description of an improved log analysis technique for use in the Athabasca oil sands deposit.

The present report provides a classification of the dominant lithofacies and regional analysis of the detailed sedimentological and stratigraphic studies, based mainly upon subsurface log and core work, with reference to ongoing outcrop work in the area.

2.2 Economics and Policy

Total remaining established reserves of crude bitumen in Alberta are estimated at more than 27 billion cubic metres (m^3), or imperial equivalent in excess of 175 billion barrels. This includes about 22.6 billion m^3 of in situ bitumen, of which 0.5 billion m^3 are from lands under active development. Surface-miuneable crude bitumen reserves amount to 5.2 billion m^3, of which 1.4 billion m^3 are from lands under active development. In 1999 synthetic crude oil production was 18.8 million cubic metres from projects in the surface mineable area of the Athabasca oil sands deposit. This compares with an estimate in Alberta of 0.3 billion cubic metres for total remaining established reserves of convenional crude oil in Alberta (AEUB, 2000c).

The major bitumen reserves of Alberta are hosted within four major oil sands deposits in northern Alberta, the Athabasca, Wabasca, Cold Lake, and Peace River deposits (Figure 1). Note, in the past, many workers have grouped the Wabasca and Athabasca deposits together as the Athabasca deposit. Using this grouping the Wabasca deposit was considered to be the West Athabasca (cf. Wightman *et al.*, 1995) (Figure 2). In the present publication, discussions of the Athabasca deposit includes Athabasca North and Central, and excludes Athabasca South and Athabasca West (Wabasca).

In 1995 the Alberta government announced a new oil sands royalty system, that demonstrates the province's commitment to development of the oil sands. A more generic, 'resource rent' style of royalty, intends to provide a more favourable fiscal climate to support major development of this vast resource. Coupled with this changed fiscal regime is an improved technological climate, resulting from horizontal drilling technology and improved in situ techniques for bitumen recovery, as well as more selective truck and shovel methods in the surface mineable area. In September 1999 a dedicated issue of the Journal of Canadian Petroleum Technology, "The Canadian Advantage: Oil Sands," highlighted some of these improved methods of in situ and mining operations (Newello, 1999). Overviews included a discussion of Suncor's Project Millenium (George, 1999); updates on the UTF project (Ito and Suzuki, 1999; Komery *et al.*, 1999; O'Rourke *et al.*, 1999); secondary bitumen recovery from tailings (Cheng *et al.*, 1999); and, permeability damage effects associated with thermal recovery at Cold Lake (Zhou *et al.*, 1999). Some factors that may impede development are the regional persistence of shale breaks, the lack of continuity of reservoir sands, and the co-production of gas and bitumen zones within

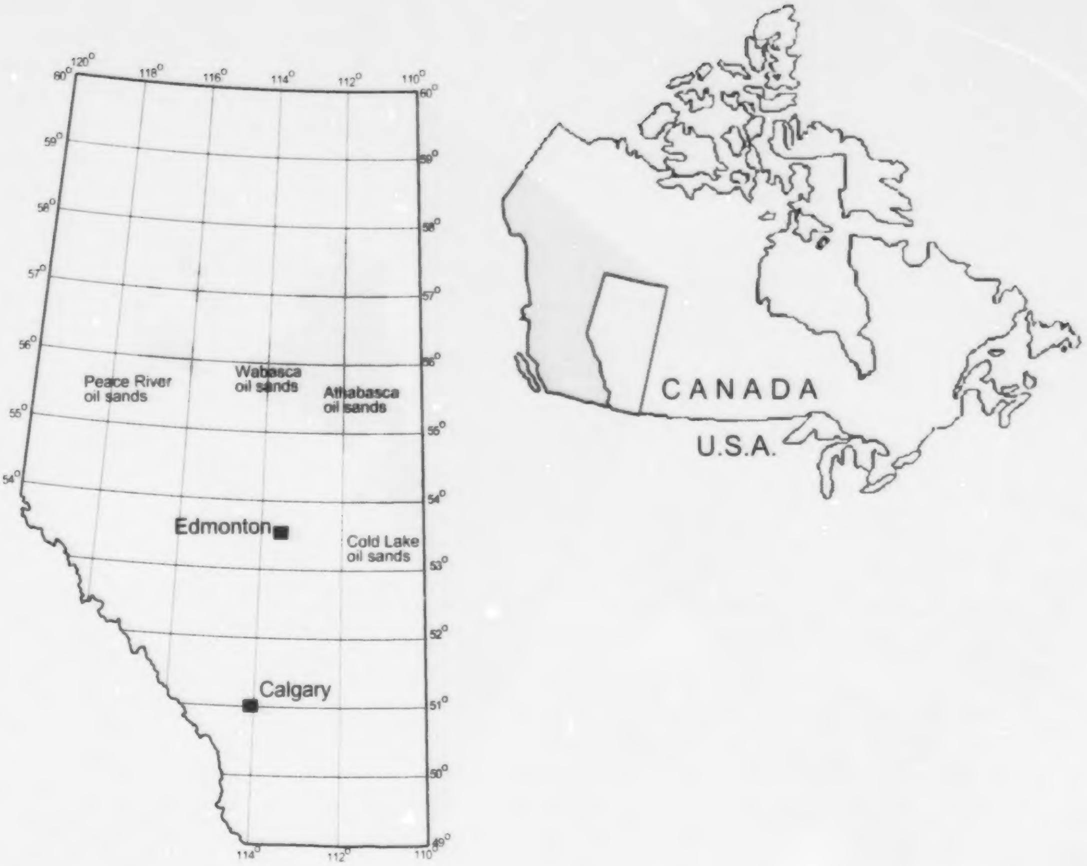

120°
118°
116°
114°
112°
110°
60°
59°
58°
57°
56°
55°
54°
53°
52°
51°
50°
49°
Peace River oil sands
Wabasca oil sands
Athabasca oil sands
Edmonton
Cold Lake oil sands
Calgary
114°
112°
110°
CANADA
U.S.A.

Figure 1: Location map of the Athabasca, Cold Lake, Peace River and Wabasca oil sands deposits

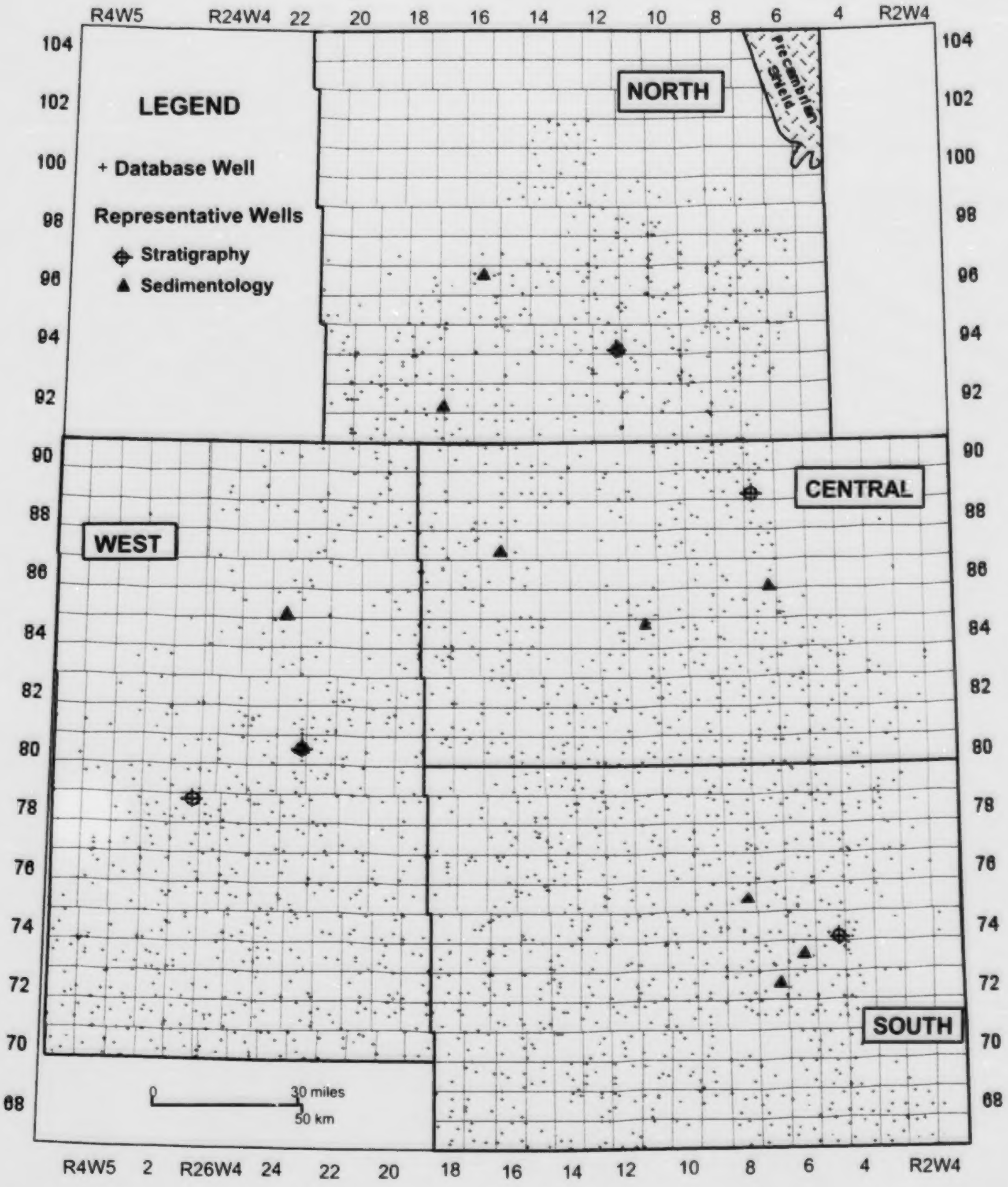

R4W5
R24W4
22
20
18
16
14
12
10
8
6
4
R2W4
104
102
100
98
96
94
92
90
88
86
84
82
80
78
76
74
72
70
68
LEGEND
+ Database Well
Representative Wells
⌖ Stratigraphy
▲ Sedimentology
NORTH
Precambrian Shield
CENTRAL
WEST
SOUTH
0
30 miles
50 km
R4W5
2
R26W4
24
22
20
18
16
14
12
10
8
6
4
R2W4

Figure 2: Map showing boundaries of Athabasca North, Central, South and West as used previously by the Alberta Geological Survey (from Wightman *et al.*, 1995).

the same reservoir. To meet some of these challenges for development, it is imperative that the natural heterogeneity of the deposits be mapped at an intermediate and local scale.

Despite the fluctuating prices of crude oil, heavy oil and bitumen, billions of dollars are being invested in Alberta's oil sands and heavy-oil fields. This is because of the 'spread' of upgrading. This spread is the price difference between an upgrader's heavy crude feedstock and its light sweet synthetic crude that can be processed by conventional refineries. Thus, in addition to the amount of exploration and scientific effort, the economics of the situation represents one of the largest investments by many oil companies in the province. An estimated projected investment of C$15.9 billion is dedicated to exploration, development, and improvement of extraction methods for mining of oil sands from the Athabasca deposit (Appendix 1). This compares with C$8.4 billion for in situ underground extraction, including reported values of C$3.3 billion for the Athabasca, C$4.4 billion for the Cold Lake, and C$0.2 billion for the Peace River oil sands deposits (Appendix 1)(Alberta Oil Sands Developers, Oilweek Magazine, 1999).

2.3 Environmental Issues

Industry and government have committed themselves to address environmental concerns. Efforts to reduce sulfur dioxide and carbon dioxide emissions have seen a 70-75% reduction in SO_2 emissions, and a 20-25% reduction in CO_2 emissions (Fort McMurray Oil Sands Interpretive Centre, 1998; Syncrude Canada,1998). Other concerns involve holding the line on greenhouse gas emissions while increasing production, reducing energy consumption per unit of production, decreasing water use through recycling, and reduction of water discharge into surrounding rivers. Ongoing work by researchers at the Alberta Geological Survey and the Alberta Research Council involves assessing geological media in the province as potential sites for storage and disposal of harmful gases from industrial plant emissions, in an effort to support Canada's commitment to cut greenhouse gas emissions.

These efforts along with recent developments in horizontal drilling, Stream Assisted Gravity Drainage (SAGD), and warm-water technologies indicate the possibility of 'environmentally-friendly' development of the oil sands. Reclamation efforts are being done in cooperation with the Fort MacKay First Nation, including waste and tailings management, recycling, forestry, bison ranching, development of parkland and trails for outdoor recreation, and fishing industries (cf. Syncrude, 1997, 1998). Ongoing hearings and applications at the Alberta Energy and Utilities Board are addressing environmental and developmental aspects of the oil sands, including groundwater and other surface water quality and management, and impacts of the co-production of subsurface gas and bitumen (cf. AEUB, 1998b, 2000a, b).

2.4 Geologic Data Coverage

The Athabasca deposit is the largest and most accessible of the oil sands deposits in northeast Alberta, occurring in an area in excess of 42,340 square kilometres and covered by an overburden of muskeg, glacial sediment, and barren sandstone and shale. A present-day incised fluvial drainage system dissects the overburden and oil sands, exposing excellent outcrops along the river courses in the Fort McMurray area. In areas of thin overburden (< 75 m), along the Athabasca River drainage network, surface mining is economic for bitumen recovery and stripped mine-faces show excellent exposures of the oil sands deposit. In the Athabasca oil sands area, extensive drilling over the past 40 years has resulted in thousands of wells (often closely spaced). Of these wells about 2400 have core from the Wabiskaw/McMurray interval, which are stored at the Alberta Energy and Utilities Board Core Research Centre in Calgary. This extensive exploration and development effort has resulted in a very large data set of available core, geophysical logs and core analyses.

2.5 Problems Pertaining to Facies Classification of the Oil Sands

As observed during the present field studies some lithofacies persist over broad areas, whereas at the same time, other lithofacies may be laterally (or vertically) discontinuous, with a high degree of local variation in sedimentary structures, fossil assemblage content, degrees and type of bioturbation. Most notably some lithofacies that have been described in outcrop have never been encountered by mine-site geologists in thousands of subsurface drill holes or kilometres of mine faces that have been logged over the years. This indicates that there is, to a certain extent, a high degree of natural complexity to the package of units that are preserved in the Athabasca deposit. As stated succinctly by McPhee and Ranger (1998): :"A... difficulty is the complex geology of the deposits [and] ... understanding the stratigraphy and sedimentology of the reservoir sands in the subsurface remains a difficult exercise. This hinders exploitation from both regional exploration aspects, as well as site specific production and development."

Published syntheses (cf. McPhee and Ranger, 1998; Wightman and Pemberton, 1997; Wightman *et al.*, 1995) are at too broad a scale to have direct application to individual areas of exploration. Detailed reservoir characterization is required to compliment advancing technologies involving horizontal drilling, SAGD, and other in situ techniques. In the surface mineable areas improved truck-and-shovel methods (that selectively strip areas to within 3 metres of vertical resolution) also require detailed lithological information.

In 1995 a preliminary regional facies scheme was proposed by Wightman *et al.*(1995). However, since that time extensive drilling with better core-data coverage has been completed in the area. Other problems of existing published facies classifications are that they tend to be developed for one area of the Athabasca deposit (i.e. southern, central, northern or western regions) but do not have direct application to other areas of the deposit. Additionally, facies in one area have a specific designation that differs from an identical facies elsewhere within the Athabasca deposit. Thus, there is little correspondence between existing facies schemes developed by different workers in the same general area. There is a clear need for a regional framework for the Athabasca Oil Sands deposit that takes into account a unified facies classification that can be applied to areas for in situ technological development, as well as for integration of data from outcrop, surface mineable and subsurface areas.

Another caveat may apply to the complexity of the units. Although it is well known by geologists working in the area, that the oil sands of the Athabasca deposit are inherently complex, not all of this complexity may be attributable solely to geological factors, but may partially reflect a difference in approaches and techniques used by different workers. For example, in the surface mineable area of the Athabasca North deposit the lithofacies scheme used by Syncrude geologists includes over 100 facies codes, of which about 60 facies are considered dominant. By contrast, the scheme used by Suncor geologists in the same area is more simplistic and interpretive, with about 18 facies, based on a combination of grade and lithofacies criteria. Other company geologists (as partners in Syncrude) have an interpretive scheme that addresses both lithofacies and sequence stratigraphic concepts, but it is unclear how this relates to the more specific lithofacies scheme used by Syncrude geologists.

3.0 PURPOSE AND PROCEDURE

The purpose of the present study is to establish a unified lithofacies classification for the McMurray Formation of the Athabasca Oil Sand deposit, using as a basis both outcrop and subsurface examples. An assessment of the existing Athabasca Oil Sands Database (Berezniuk *et al.*, 1997) indicated that the database, with a resolution of 4 wells per township, was at too coarse a scale to adequately describe facies trends, particularly with potential applications to in situ technologies. Thus, one of the aims of the present and ongoing work at the Alberta Geological Survey is to increase the scale of resolution to 1 well per section, where data allow this detail.

In the past, regional stratigraphic markers (cf. Appendix 2), cross sections and maps were prepared, using the Athabasca oil sands database to properly set the stratigraphic framework. Present stratigraphic data coverage exceeds 4,000 points, nearly doubling the coverage of the database (cf. Wynne *et al.*, 1994). In the establishment of this regional lithofacies classification, a broad view is taken of the whole Athabasca deposit (except Athabasca West (Wabasca)), from Townships 80 to 104, and Ranges 1W4 to 18W4, inclusive. Lithofacies were defined after detailed section measuring of both core and outcrop, and by comparisons with core photographs from sites not specifically measured in the present study. Lithofacies are defined with particular emphasis on lithology, grain size, bed thickness, contacts, physical sedimentary structures, degree of bioturbation, type of trace fossils, and clast composition. In total, detailed sections were measured for 45 outcrops and 145 cores (Figure 3a and b; Appendix 3).

In the present publication, the facies classification is given as a detailed catalogue of each facies, with an explicit text description, representative photographs from core and outcrop, and typical geophysical log motifs. Where discernable, vertical and lateral facies associations, and stacking patterns are discussed, along with paleogeographic and sequence stratigraphic interpretations. In summary, facies models are presented for internal subdivisions within the McMurray Formation, with discussions of potential application to petroleum geology.

4.0 STRATIGRAPHIC FRAMEWORK AND GEOLOGIC SETTING

A table of formations illustrating the primary oil sands and heavy oil horizons in Alberta with a type well geophysical-log motif for the McMurray/Wabiskaw to Clearwater interval is given in Figures 4 and 5. Regional maps including unconformity structure and residual, McMurray Formation structure and isopachs are given in Figures 6a, 6b, 7 to 9.

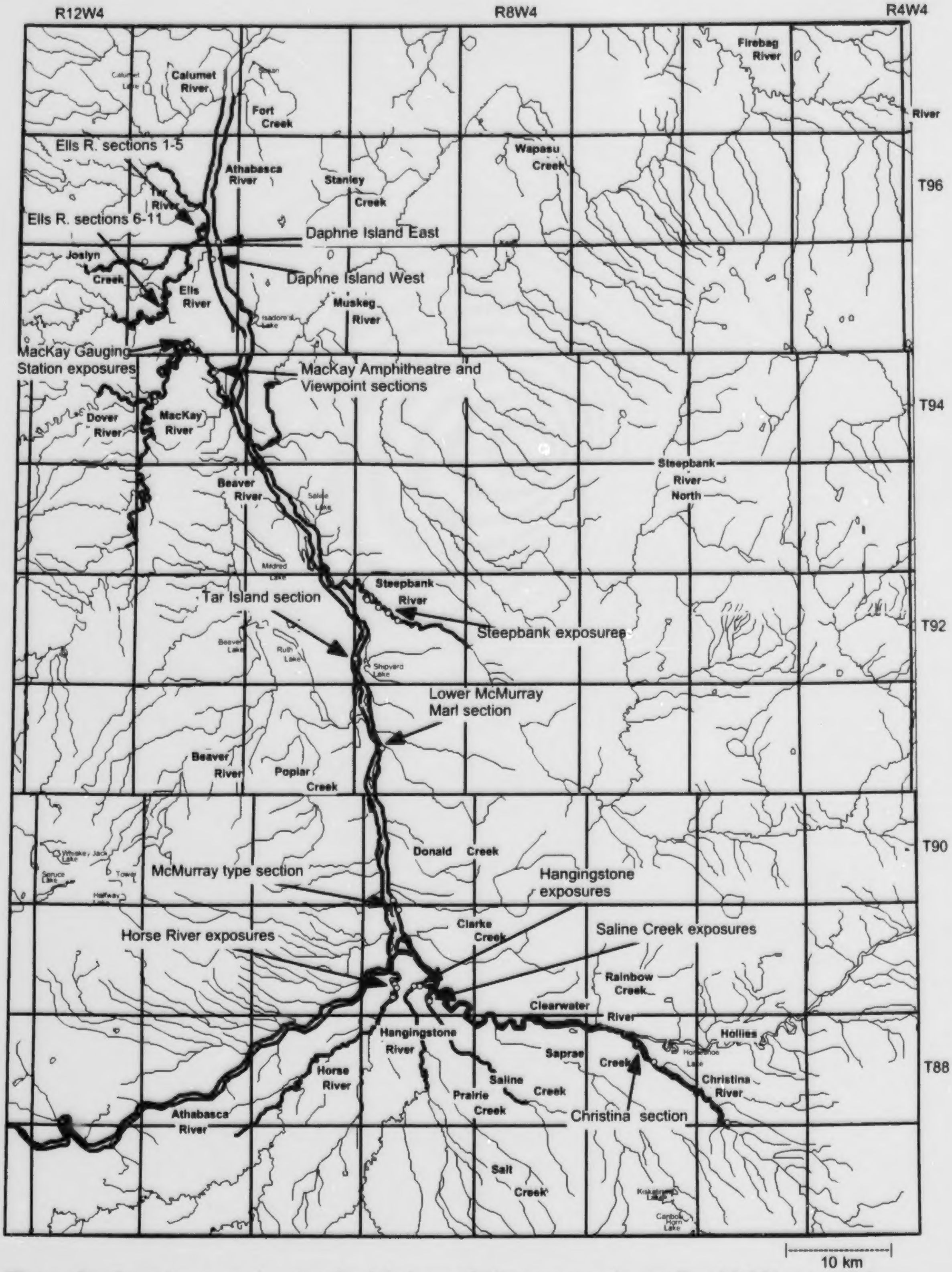

R12W4
R8W4
R4W4
T96
T94
T92
T90
T88
Calumet Lake
Calumet River
Fort Creek
Firebag River
River
Ells R. sections 1-5
Athabasca River
Stanley Creek
Wapasu Creek
Tar River
Ells R. sections 6-11
Daphne Island East
Joslyn Creek
Daphne Island West
Ells River
Isadore's Lake
Muskeg River
MacKay Gauging Station exposures
MacKay Amphitheatre and Viewpoint sections
Dover River
MacKay River
Beaver River
Saline Lake
Steepbank River North
Mildred Lake
Steepbank River
Tar Island section
Steepbank exposures
Beaver Lake
Ruth Lake
Shipyard Lake
Lower McMurray Marl section
Beaver River
Poplar Creek
Whiskey Jack Lake
Tower
Spruce Lake
Halfway Lake
Donald Creek
McMurray type section
Hangingstone exposures
Clarke Creek
Horse River exposures
Saline Creek exposures
Rainbow Creek
Clearwater River
Hangingstone River
Hollies
Saprae Creek
Horseshoe Lake
Horse River
Saline Creek
Christina River
Prairie Creek
Athabasca River
Christina section
Salt Creek
Kiskatinaw Lake
Canbou Horn Lake
10 km

Figure 3a: Overview map showing the Athabasca drainage network near Fort McMurray and the location of measured sections along the Athabasca River and associated tributaries.

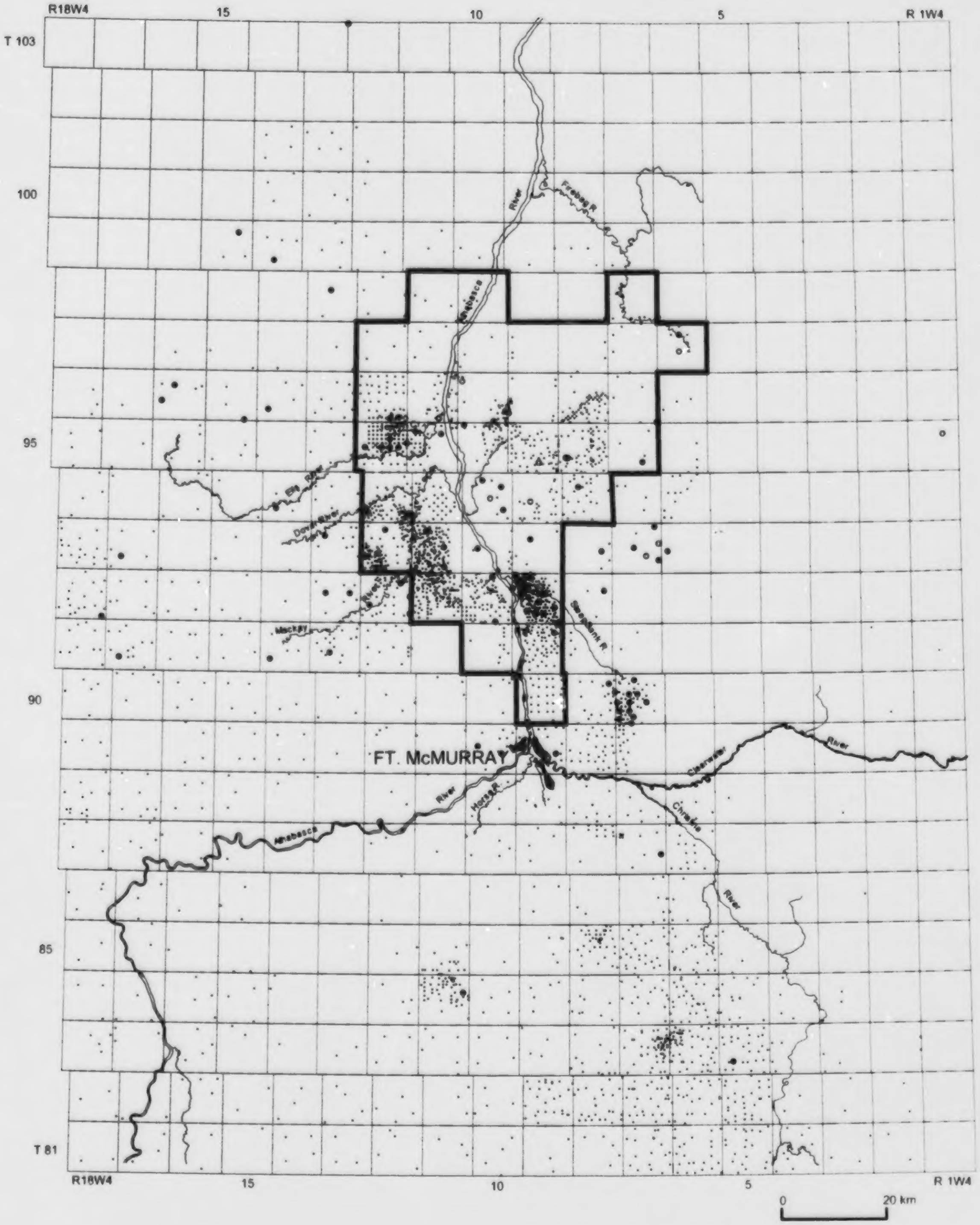

R18W4
15
10
5
R 1W4
T 103
100
95
90
85
T 81
Athabasca River
Firebag R.
Ells River
Dover River
Steepbank R.
Mackay
FT. McMURRAY
Horse R.
Clearwater River
Christina River
0
20 km

Figure 3b: Study Area and well distribution. Smaller circles represent Athabasca Oil Sands database wells and the larger circles represent described cores.

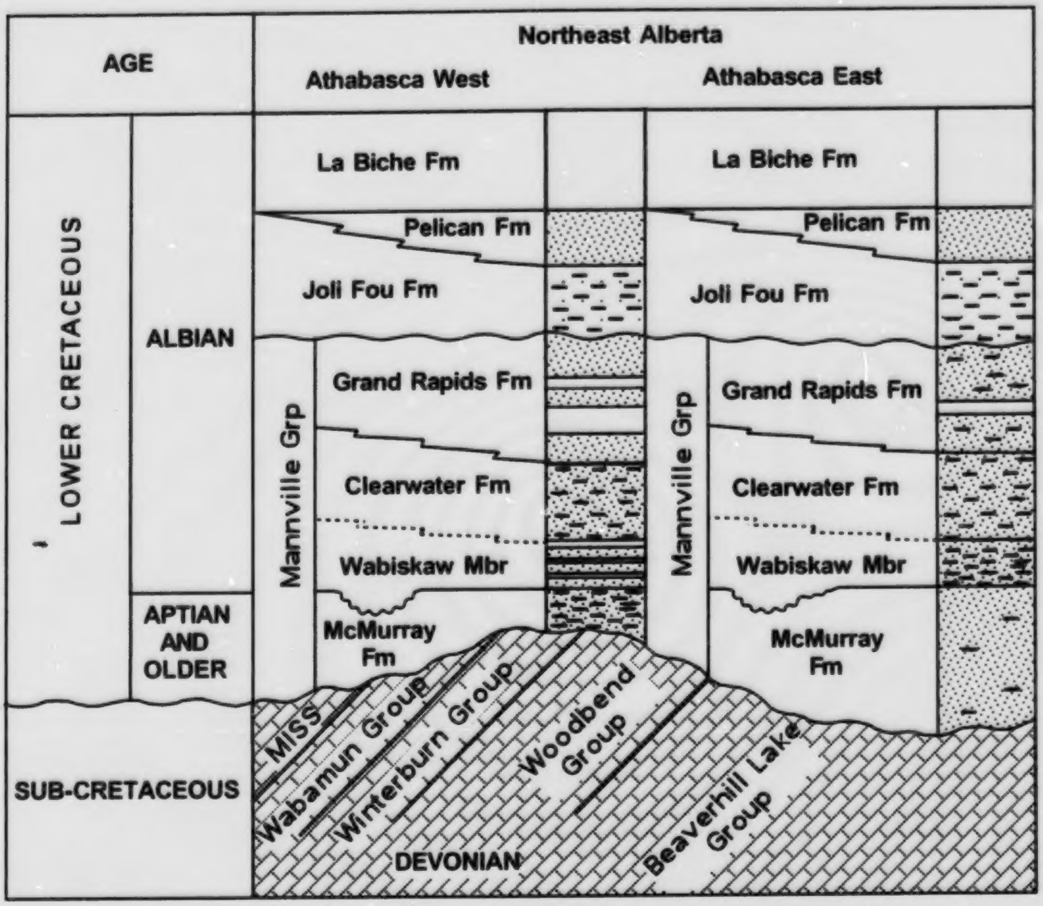

AGE
Northeast Alberta
Athabasca West
Athabasca East
LOWER CRETACEOUS
ALBIAN
APTIAN AND OLDER
SUB-CRETACEOUS
La Biche Fm
Pelican Fm
Joli Fou Fm
Mannville Grp
Grand Rapids Fm
Clearwater Fm
Wabiskaw Mbr
McMurray Fm
MISS
Wabamun Group
Winterburn Group
Woodbend Group
Beaverhill Lake Group
DEVONIAN

Figure 4: Schematic Cross Section, Fort McMurray area *(modified from Wightman et. al 1995)*

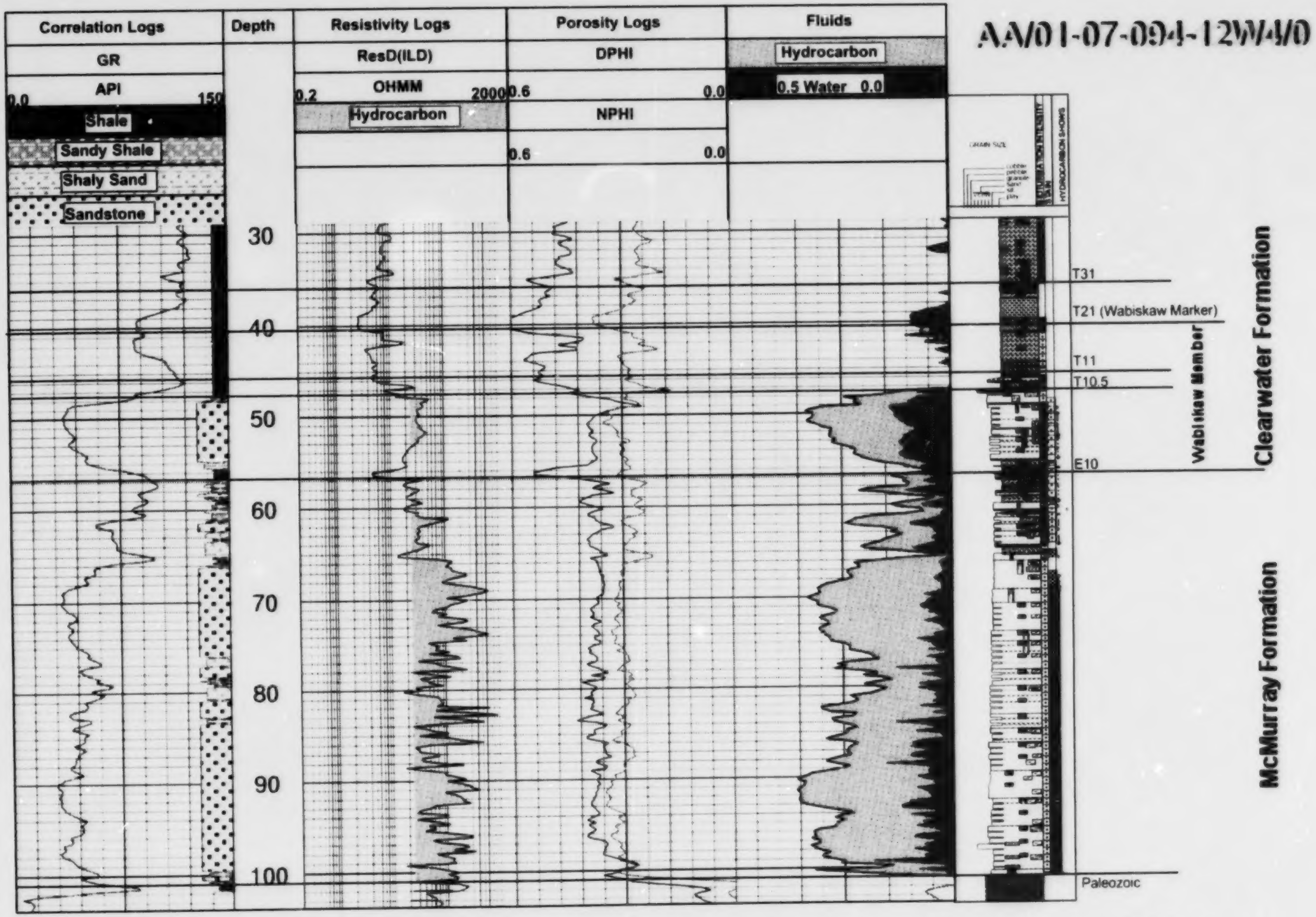


Figure 5: Stratigraphic column with geophysical log motifs showing representative gamma ray (GR), resistivity (RESD(ILD)), density porosity (DPHI), neutron porosity (NPHI), hyrocarbon fluids and water. T and E markers are given in Appendix 2.

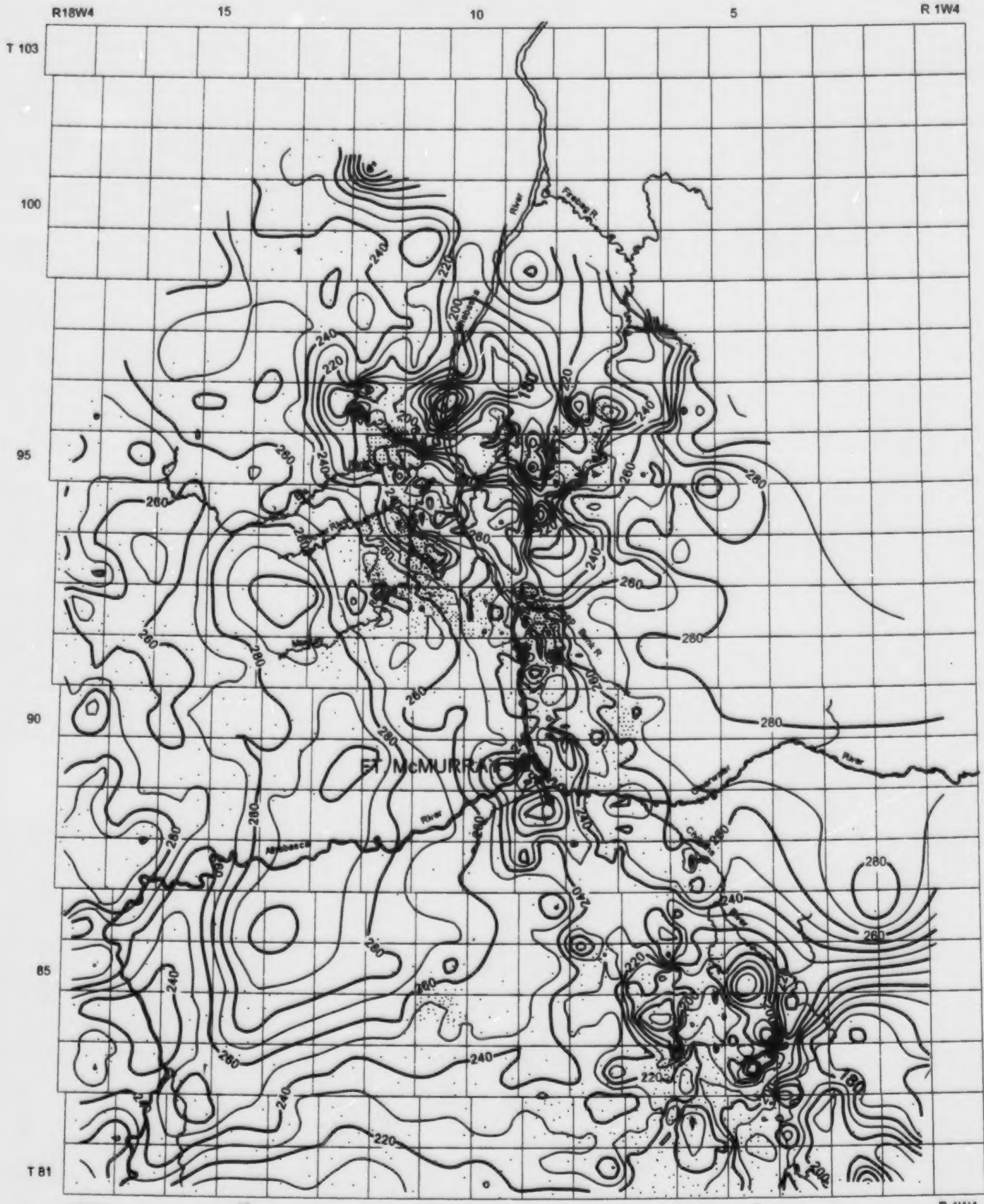

R18W4
15
10
5
R 1W4
T 103
100
95
90
85
T 81
Firebag R.
River
Athabasca
FT. McMURRAY
Clearwater
River
Steepbank R.
200
220
240
260
280
180
0
20 km

Figure 6a: Structure on the pre-Cretaceous unconformity. Contour interval is 10m.

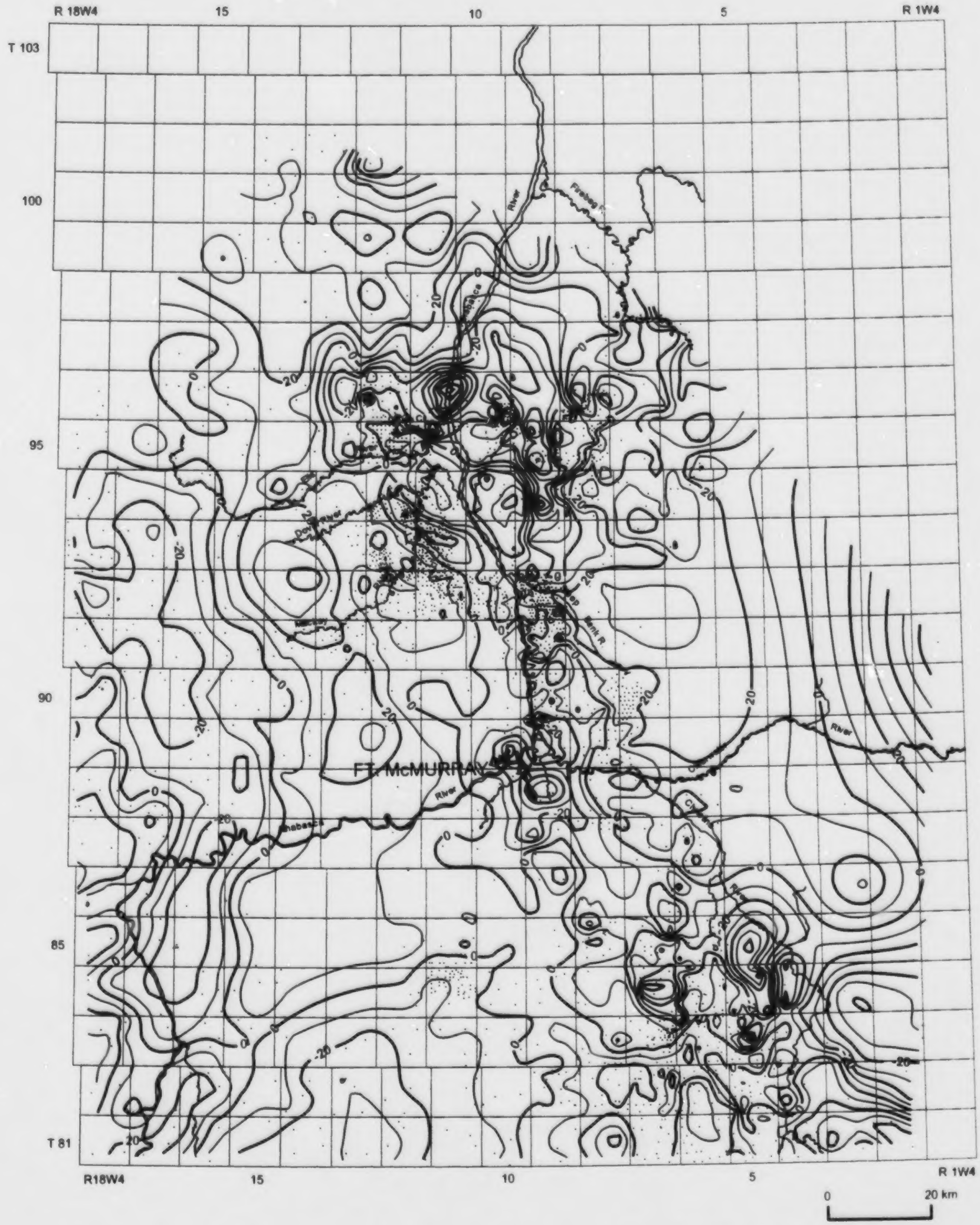

R 18W4
15
10
5
R 1W4
T 103
100
95
90
85
T 81
R18W4
15
10
5
R 1W4
FT. McMURRAY
Athabasca
River
Firebag R.
0
20
-20
0
20 km

Figure 6b: Third order residual on the pre-Cretaceous unconformity showing positive and negative relief. Contour interval is 10m.

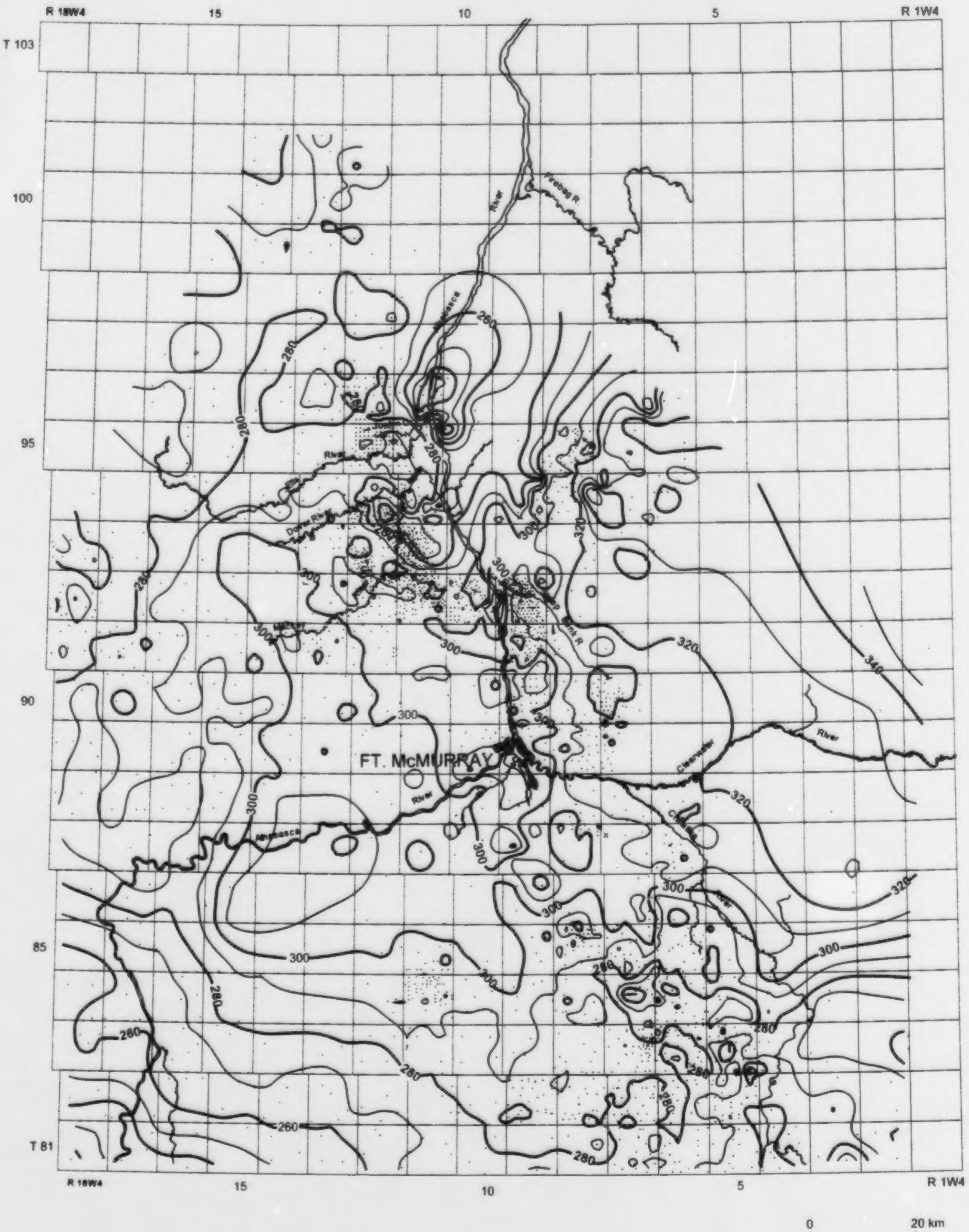

R 18W4
15
10
5
R 1W4
T 103
100
95
90
85
T 81
Firebag R.
Athabasca River
Dover River
Steepbank R.
Clearwater River
Christina River
FT. McMURRAY
260
280
300
320
340
0
20 km

Figure 7: Structure on the McMurray Formation. Contour interval is 10m.

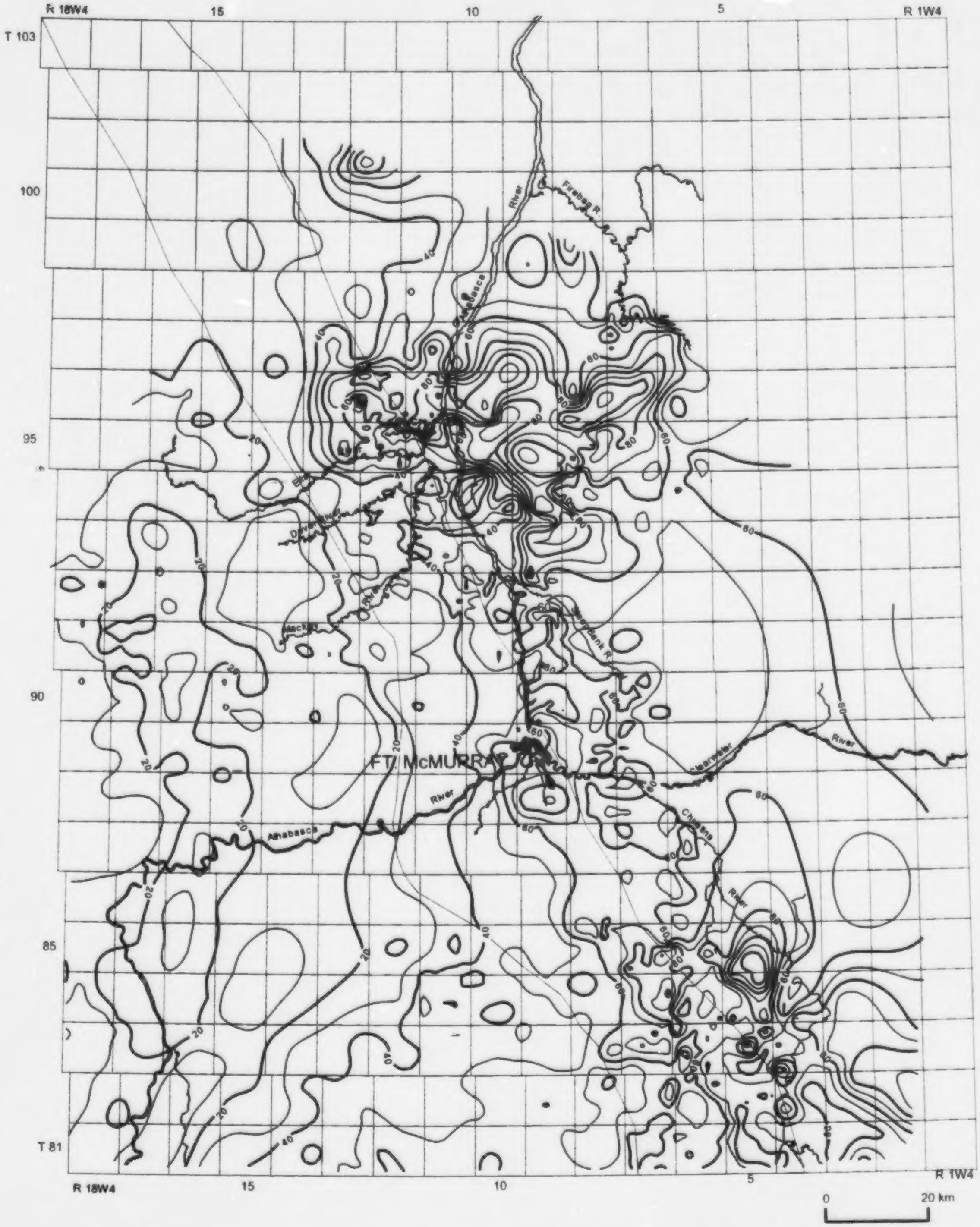

R 18W4
15
10
5
R 1W4
T 103
100
95
90
85
T 81
Firebag R.
Athabasca River
Ells
Dover River
MacKay
Steepbank R.
FT. McMURRAY
Clearwater River
Athabasca River
Christina River
20
40
60
0
20 km

Figure 8: McMurray Formation Isopach. Contour interval is 10m. The shaded area shows the salt scarp

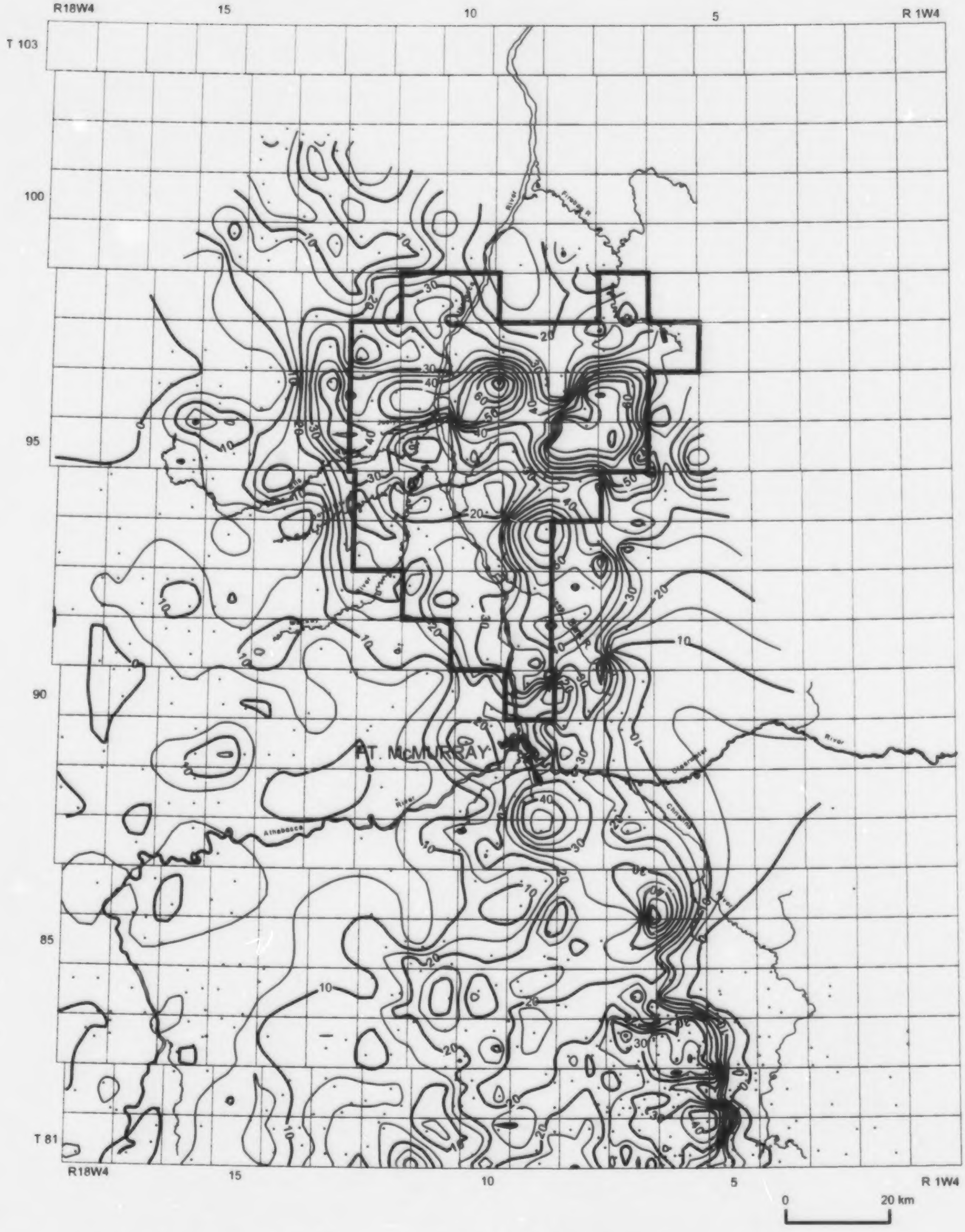

R18W4
15
10
5
R 1W4
T 103
100
95
90
85
T 81
FT. McMURRAY
Athabasca
River
Firebag R.
Clearwater
River
0
20 km
10
20
30
40
50
60

Figure 9: Greater than 6% tarmass in the McMurray Formation. Contour interval is 10m. The surface mineable area is highlighted

4.1 Devonian Units

In the study area, the McMurray Formation unconformably overlies Devonian carbonates of the Beaverhill Lake and Woodbend groups. The Christina and Moberly members of the Waterways Formation (Beaverhill Lake Group) outcrop along the Athabasca River and associated tributaries. In the eastern portion of the study area the Winnepegosis (locally called Methys) Formation of the Elk Point Group outcrops along the Firebag River. The Devonian units form a series of northwest-trending subcrop belts, with significant relief on the pre-Cretaceous unconformity that reflects a long period of subaerial exposure and erosion prior to emplacement of the Lower Cretaceous succession (Figures 6a and 6b). Numerous limestone outcrops of the Moberly Member (less commonly the Christina Member) occur along present day river drainages in the study area. Local karstification of the Devonian carbonates and mineralization (including pyrite, chalcopyrite, sphalerite, siderite; less commonly barite, calcite, quartz and silica, among others) occurs along the unconformity (Abercrombie, 1998; Abercrombie and Feng, 1997; Feng and Abercrombie, 1994; Tsang, 1998, and see further discussion in Section 4.3.2.1).

4.2 pre-Cretaceous Unconformity

The regional pre-Cretaceous unconformity in northeast Alberta is comprised of a series of subcropping, westerly dipping formations of Middle and Upper Devonian age that become younger from east to west. Differential erosion of the variably argillaceous carbonate units combined with tectonic collapse caused by dissolution of Elk Point Group evaporites has resulted in several prominent structural anomalies on the unconformity surface (Figures 6 and 9, cf. McPhee and Wightman, 1991, and This Study). Positive structural elements include the Grosmont High consisting of two resistant northwest trending ridges (Grosmont Formation) and a curvilinear high to the east comprised of carbonates of the Waterways Formation. A regional, linear depression, called the Prairie Salt Scarp, trends roughly parallel to the strike of the subcropping Devonian units, reflecting regional dissolution of evaporites within the Elk Point Group (Figure 6).

Collapse of the overlying carbonate units within the Waterways succession can be recognized in outcrop exposed along the present-day drainage network and as well in subsurface cores. Associated with the carbonate collapse is the development of paleokarst features along the unconformity, including sinkholes, brecciation, and small-scale folding and faulting in areas proximal to the dissolution front. In the north, the Prairie Salt Scarp widens and deepens significantly into a somewhat circular depression, locally known as the Bitumount Basin (Figure 6). The highly variable structural and erosional relief on the pre-Cretaceous unconformity greatly influenced sediment dispersal patterns and the facies architecture of the overlying Lower Cretaceous units, particularly the McMurray Formation and the Wabiskaw Member of the Clearwater Formation (Figures 8, 9).

A structure and third-order residual map best illustrates the regional topography on the pre-Cretaceous unconformity (Figures 6a and 6b). A series of paleotopographic highs and lows trend north- northwesterly, with the most easterly linear trough correlating with the evaporite-dissolution zone in underlying bedrock (Figures 6b, 7). Gradients are steepest along the margins of the Bitumont Basin (Townships 95 to 98, Ranges 7W4 to 13W4 Meridian).

4.3 Lower Cretaceous Units and Contacts

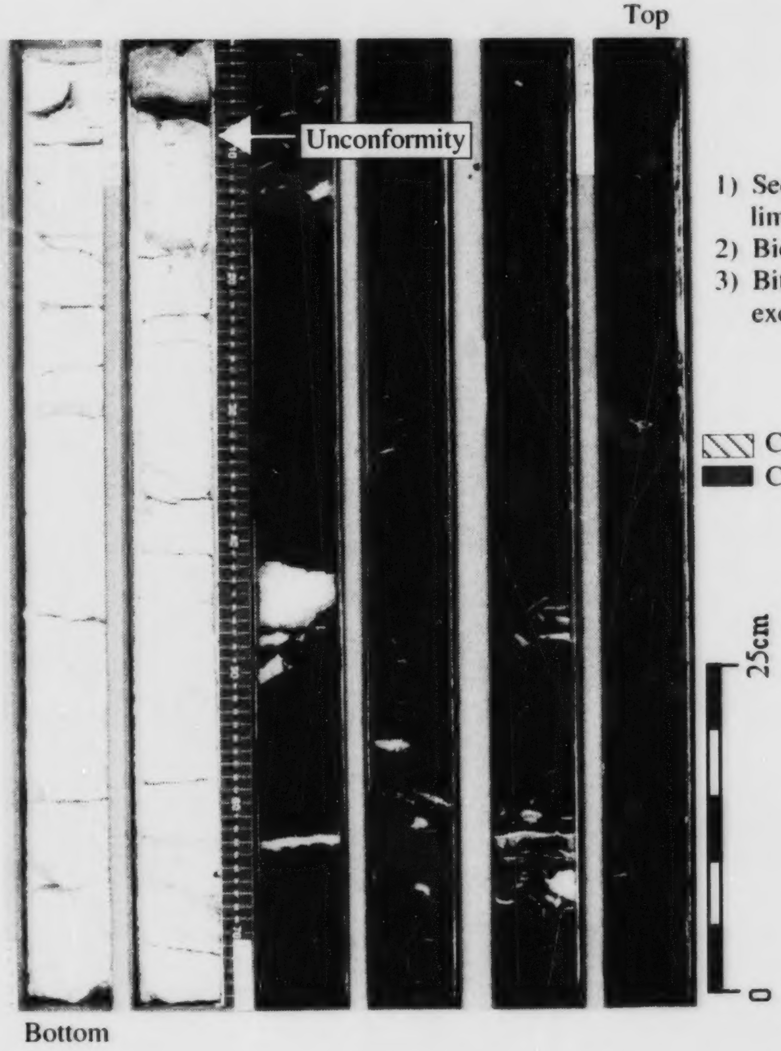
Lower Cretaceous siliciclastic sediment overlies the regional pre-Cretaceous unconformity. Thickness variations within the Lower Cretaceous reflect primarily a combination of topography on the pre-Cretaceous unconformity, and the preservation beneath the Quaternary erosion surface. The Lower Cretaceous Mannville Group succession is divided into the following ascending formations: the McMurray, Clearwater and Grand Rapids. Four resource based divisions for the Lower Cretaceous deposits are designated by the AEUB in the Athabasca Oil Sands area, comprising in ascending order: the McMurray/Wabiskaw, Lower Grand Rapids, Middle Grand Rapids, and Upper Grand Rapids (Figure 4) (cf. Kramers and Prost, 1986; MacGillivray and Brady, 1996). Of these units, the bulk of the bitumen and gas reserves are contained within the McMurray/Wabiskaw interval in the Athabasca Oil Sands area (Figure 9). From a regulatory viewpoint the Wabiskaw and McMurray are considered as a single unit because of the connectivity between the two units, that are often in direct contact or later co-mingled for production (cf. MacGillivray and Brady, 1996). Geologically, however, these are dissimilar units, each with distinct lithologies, deposited within unlike environments of different ages (biostratigraphically-dated). Thus, the McMurray Formation rests with profound unconformity on the Devonian carbonates, and is unconformably overlain by the Wabiskaw Member (Clearwater Formation).

In the present study mixed carbonate and calci-/siliciclastic units emplaced along the basal unconformity were included in the lithofacies classification; however, the facies analysis did not extend above the McMurray/Wabiskaw contact. The lowermost units along the basal unconformity were incorporated because palynological analysis indicates that some of the mixed calci-/siliciclastic units were emplaced as karst fill and colluvium along the pre-Cretaceous unconformity surface during McMurray time. Thus the lithofacies classification applies to units bounded by the pre-Cretaceous unconformity at the base, and the upper contact of the McMurray Formation/Wabiskaw Member at the top.

4.3.1 Basal Unconformity of the McMurray Formation

The Lower Cretaceous McMurray Formation is bounded at the base by a regional unconformity that juxtaposes weathered, argillaceous Devonian carbonates against siliciclastic sediments of the McMurray Formation. Identifying this contact in the subsurface on geophysical logs is generally easy due to the sharp contrast in density from carbonates to unconsolidated siliciclastics (Pz, Figures 10 and 11). The base of the McMurray is difficult to discern where bitumen-bearing clastics occur as karst-infill within the surrounding carbonates beneath the sub-Cretaceous unconformity. Other complicating factors include the local occurrences of argillaceous mudstones, leached Devonian marls and paleosols (Figure 12).

The nature of the basal unconformity is generally sharp, but lithologies within the underlying carbonate succession can vary at the contact. The contact may be mineralized, primarily with



1) Sedimentary Features: nodular limestone, mudstone clasts
2) Bioturbation Index: NA
3) Bitumen Saturation: very good - excellent

▨ Cored Interval
■ Core Interval Viewed

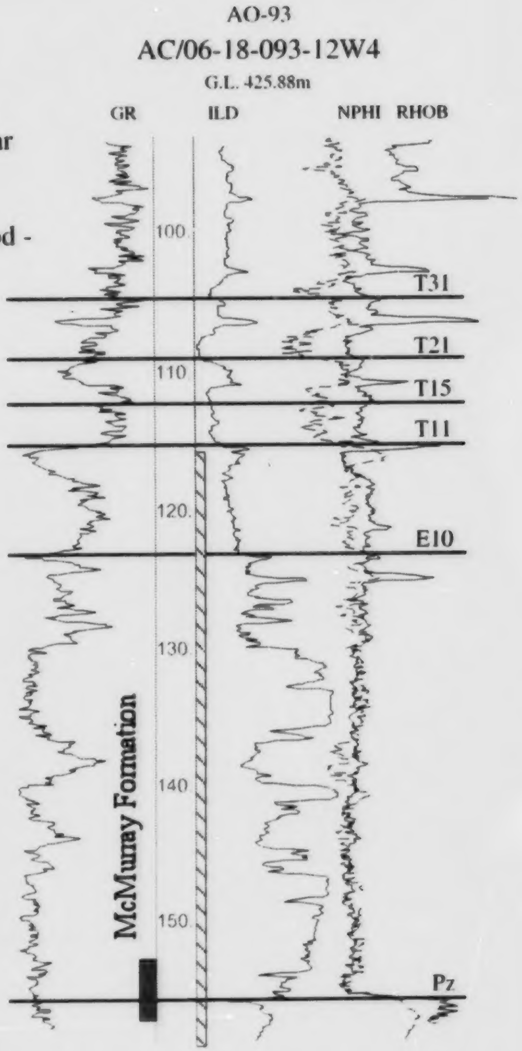


Figure 10: Pre-Cretaceous unconformity separating McMurray oil sands from nodular limestones of the Devonian Waterways Formation. Geophysical log responses shown to the right.

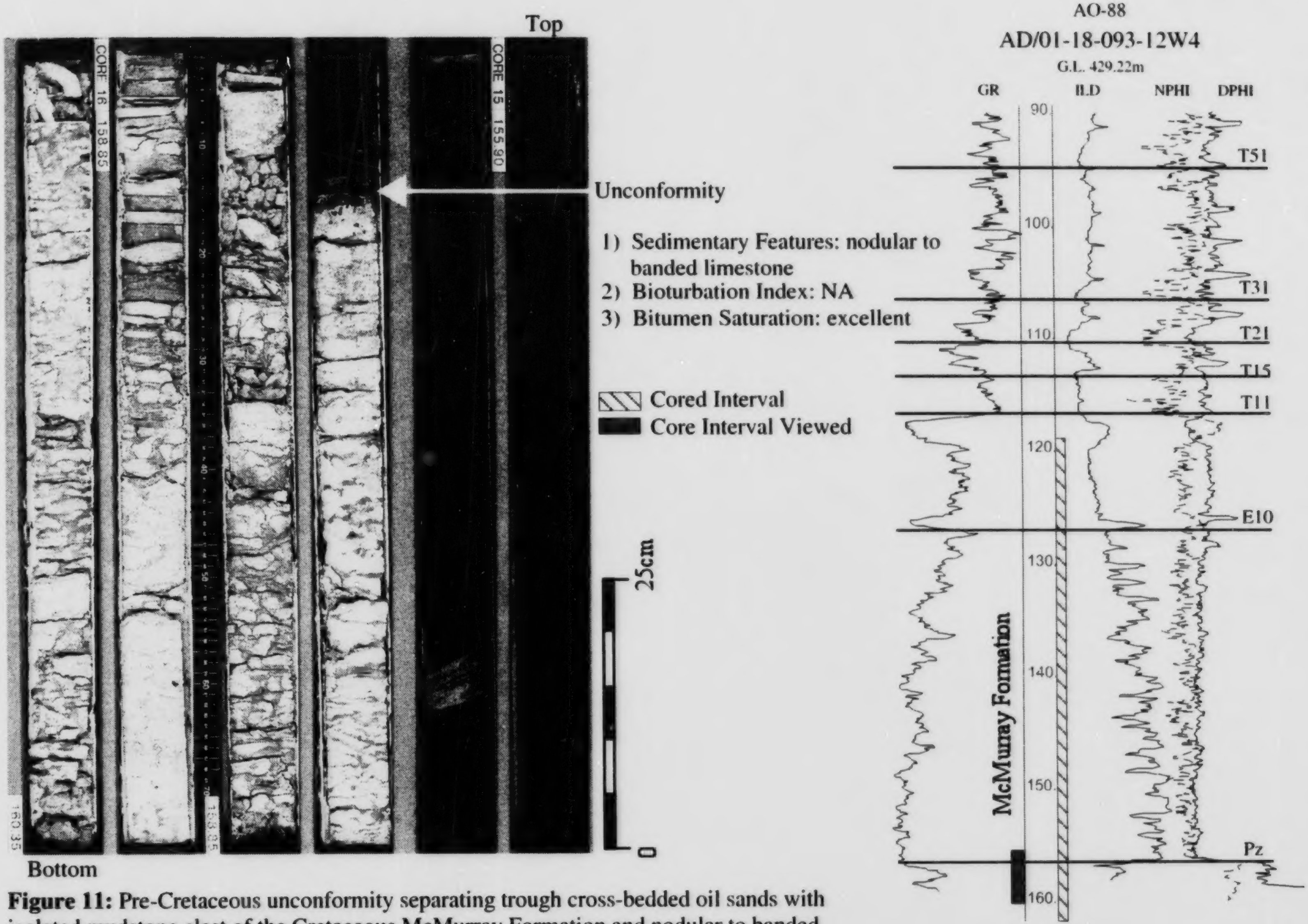

Top
CORE 15 155.90
CORE 16 158.85
158.85
160.35
Bottom
Unconformity
1) Sedimentary Features: nodular to banded limestone
2) Bioturbation Index: NA
3) Bitumen Saturation: excellent
▨ Cored Interval
■ Core Interval Viewed
25cm
0
AO-88
AD/01-18-093-12W4
G.L. 429.22m
GR
ILD
NPHI
DPHI
90
100
110
120
130
140
150
160
T51
T31
T21
T15
T11
E10
Pz
McMurray Formation

Figure 11: Pre-Cretaceous unconformity separating trough cross-bedded oil sands with isolated mudstone clast of the Cretaceous McMurray Formation and nodular to banded argillaceous limestone of the Devonian Waterways Formation. Arrow on photograph indicates the unconformity surface. Geophysical log responses shown to the right.

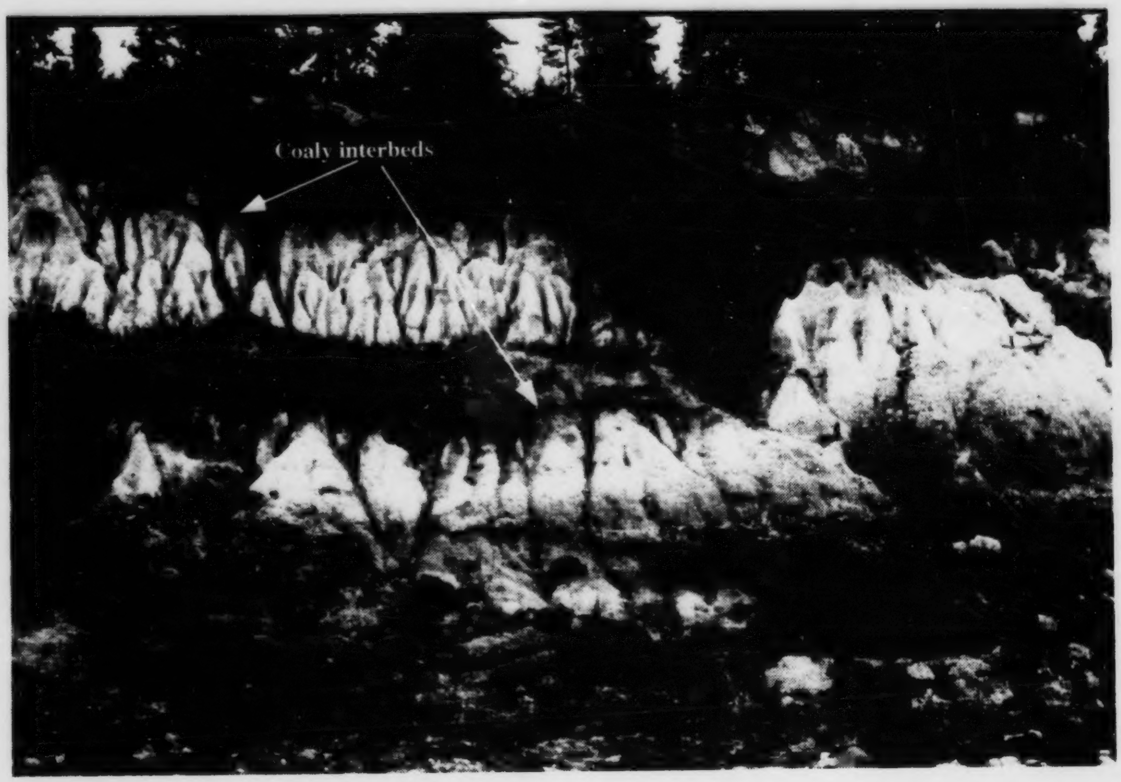


Figure 12: Mottled sandy marl with thin coaly beds occupying a paleotopographic low on the pre-Cretaceous unconformity, Lower McMurray Formation. East side of the Athabasca River, south of the confluence of the Steepbank and Athabasca rivers. Outcrop is about 5 metres high. Facies 4.

sulphides (mainly pyrite and chalcopyrite). The mineralization includes pyritized clasts, fracture fills or a simple, thin pyrite layer at the interface (cf. Figure 11). The carbonate erosional surface often displays a weathered profile of orange and orange-red that often penetrates a few metres into the Devonian limestone. Rare carbonate clasts occur along the unconformity. Along the active dissolution front and in a belt to the east occurs extensive karstification of the underlying Devonian carbonates. Karst features include isolated sinkholes, larger depressed regions and local karst breccias. Cores cut through sinkholes and other karstic features often display alternating units of collapsed carbonate breccia and associated karst-infill calci-/siliciclastic sediments that are overturned, brecciated and sometimes supported within a muddy (often calcareous) matrix.

Due to the marked contrast in lithologies across the pre-Cretaceous unconformity surface, on logs this contact can usually be easily picked unless there is significant karstification and infill of clastics down into cavities within the Devonian carbonates. Because of the local karstification effects, the quality of this log pick is variable, ranging from poor to excellent, where there are no karst features (Appendix 2).

Marly deposits and leached carbonate paleosols are less common along the unconformity surface. Such deposits most often occupy lows on the erosional surface (Figures 12, 13). In these instances accurately identifying the sub-Cretaceous unconformity surface from well logs can be problematic, particularly in localities where the McMurray succession is mudstone-dominated (mudstone on mudstone contacts). The marly lacustrine unit generally lacks bioturbation (may contain rare horizontal *Planolites* traces), contains carbonaceous debris, and is interpreted as alluvial in origin. Nodules along the unconformity include ironstone (siderite along with hematite). Associated with the ironstone are coarse sand, silt and clay, which are locally cemented with quartz and goethite (Mellon, 1955, 1956). Organic matter includes coal and carbonaceous shale. Microfossil dating of spores and pollen grains indicate a Barremian age, in paludal, isolated swamps along depressions on the eroded limestone surface.

4.3.2. McMurray Formation

The McMurray Formation is the lowermost siliciclastic unit within the Lower Cretaceous Mannville Group in northeast Alberta. The succession is bounded unconformably at the base and the top, and has internal disconformities, locally disrupting the McMurray succession. It is noteworthy that in other areas of Alberta and Saskatchewan the existence of intra-Mannville disconformities have been recognized and that apparent that trapping of oil occurred in relation to these features (cf. Cant and Abrahamson, 1996; Vigrass, 1977).

The basal pre-Cretaceous unconformity, as previously mentioned, has significant relief, and had a profound effect on sediment distribution and depositional facies patterns within the McMurray Formation. Along the present-day drainage system, and within other localized areas in the subsurface, the top of the McMurray Formation has been removed by post-Cretaceous erosion. The youngest of these valley incision events was during the Quaternary Period, with some Quaternary channels incising up to 300 metres into the underlying Cretaceous succession (Andriashek and Meeks, 2000; Parks and Andriashek, 2000).

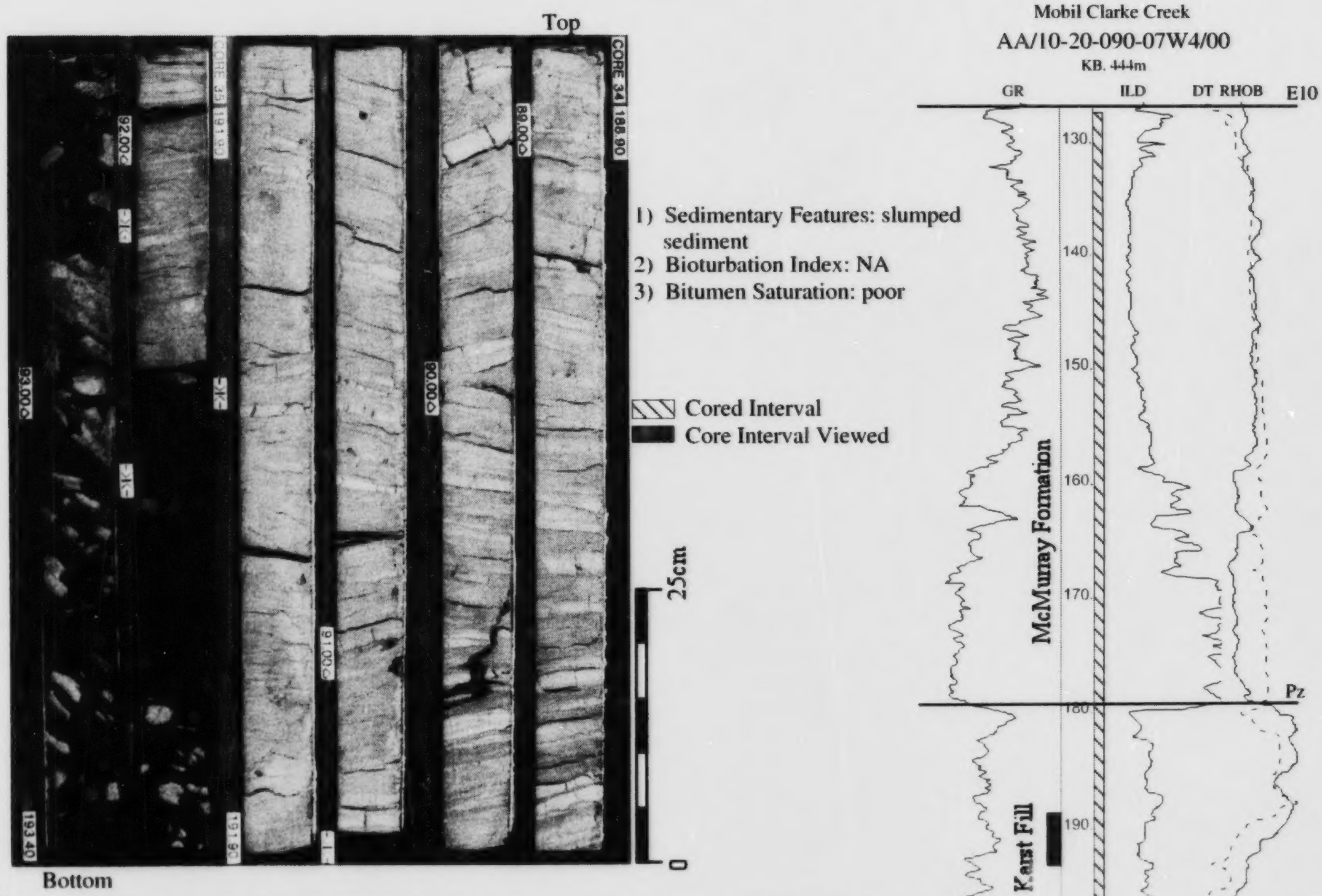

Top
CORE 34 188.90
89.00
90.00
91.00
191.90
CORE 35 191.90
92.00
93.00
193.40
Bottom
0
25cm
1) Sedimentary Features: slumped sediment
2) Bioturbation Index: NA
3) Bitumen Saturation: poor
▨ Cored Interval
■ Core Interval Viewed
Mobil Clarke Creek
AA/10-20-090-07W4/00
KB. 444m
GR
ILD
DT RHOB
E10
130
140
150
160
170
180
190
200
McMurray Formation
Pz
Karst Fill

Figure 13: Karst-fill mixed calci-/siliciclastics along the unconformity overlain by laminated calcareous mudstone. Subsequent cores above the sucession shown, displays continued, alternating siliciclastic/carbonate mixing. Geophysical log response shown to the right.

Former informal stratigraphic subdivisions for the McMurray Formation included the Lower, Middle and Upper McMurray Formation (Carrigy, 1959a,b, 1962, 1963a, b, 1966, 1967; Mellon, 1955, 1956). Earlier petrographic, paleontologic and heavy mineral work indicated some differences between these informal members. However, subsequent work shows that the distinction of the Upper and Middle informal members of the McMurray Formation is difficult using petrography and fossil content (Burden, 1984; Wightman and Pemberton, 1997; and the present study). Additionally, such observed subtle differences may reflect a predictable change upsection from estuarine to more marine conditions.

Detailed core-logging, facies and geophysical-log analysis of subsurface data during the present study indicates that, where distinctive facies or log-markers are absent, it is impossible to differentiate units that were formerly designated as Middle or Upper McMurray. Furthermore facies and biostratigraphic analyses of units formerly defined as Middle or Upper McMurray (Burden, 1984; the present study) show no difference in age, and any facies variations appear to relate to paleogeographic variations, with Middle and Upper McMurray units interpreted as different portions of the same depositional system. Thus it is recommended here that the informal term 'Middle McMurray' be abandoned, and what was formerly mapped as 'Middle McMurray' now be included as part of the Upper McMurray succession. By contrast, recognition of the Lower McMurray is usually straightforward, based on facies seen in both core and outcrop, and on geophysical-logs from subsurface wells. Thus, the two mappable informal members of the McMurray Formation recognized in the present study are the Lower McMurray and the Upper McMurray, which are separated by a disconformity. However, when working on a more detailed scale in specific areas, it may still be useful to use finer subdivisions for descriptive purposes (cf. Flach, 1984).

The McMurray Formation succession was deposited on an exposed karstic landscape of ridges and valleys, with local paleosols, and varies in thickness from being absent over Devonian highs to over 130 m thick in the Bitumount Basin. The McMurray Formation is notorious for having very complex sedimentary facies relationships that change both laterally and vertically over very short distances, which is problematic for companies exploiting the deposit. In the present study area, the thickness of the McMurray succession ranges < 10 m in the west to > 100 m in the central region (Figure 8). The highly variable topography on the basal unconformity combined, to a lesser degree, with the upper erosional surface (Wabiskaw/McMurray contact) greatly influences the thickness of the McMurray Formation. The north-south thickness trend in the McMurray Formation correlates with location of the evaporite dissolution zone, the "Prairie Evaporite Salt Scarp," running generally north-northwest from Ranges 1W4 Meridian to 8W4 Meridian, Townships 72 to 90 (Figures 7, 8). North of Fort MacKay the thickening trend of the McMurray succession has an east-west component as well from Range 7W4 Meridian to 13W4 Meridian, within Townships 94 to 96. In the western part of the regional study area, the McMurray units are < 40 metres thick (Figure 8).

4.3.2.1 Lower McMurray Formation

The Lower McMurray is a heavily channelized, fluvial-dominated succession that unconformably overlies Devonian carbonates. The Lower McMurray informal member comprises a variable succession of lacustrine mudstone/coal, associated with blocky clean sands of braided fluvial complexes, with overbank/lacustrine siltstone/mudstone and rare paleosols. Lithologically the Lower McMurray is comprised of gravel, coarse sand, silt and clay, with siderite as cement or spherulites within ferrigunous paleosols. Autocthonous coal seams are interbedded with lacustrine silty clay at the base of the succession; with allochthonous reworked organic debris now preserved as lignite/carbon detritus in the channel sands. Siderite, calcite and quartz cements are present within the sand and siltstone units, particularly in areas subjacent and adjacent to protruding Devonian carbonate paleohighs. Cemented zones are indurated and differ from the rest of the McMurray sands that are only cemented by bitumen or are unconsolidated where they are water bearing. The major grain constituents are quartz and quartzite, minor K-feldspar grains, and accessory heavy minerals including garnet, kyanite and staurolite (Carrigy, 1959a,b, 1962, 1963a, b, 1966, 1967; Mellon, 1955, 1956). Clay minerals include kaolinite and illite. Local quartz (including microcrystalline quartz or silica), siderite, calcite and pyrite cements are common (Tsang, 1998). Trace amounts of native elements and other base metal oxides are associated with siderite, silica and quartz-cemented intervals within the Lower McMurray succession. These elements include: gold, silver, nickle, platinum, titanium-oxide (probably anatase), and zirconium-oxide (cf. Abercrombie, 1998; Abercrombie and Feng, 1997; Feng and Abercrombie, 1994; Tsang, 1998). One sample assayed at 400 ppb Au (cf. Abercrombie, 1998 pers. Comm. Cited in Tsang, 1998). Studies of diagenetic textures indicate that many of these metals and oxides were precipitated prior to the emplacement of hydrocarbons within the McMurray succession (cf. Tsang, 1998).

4.3.2.2 Upper McMurray Formation

The Upper McMurray is a heavily channelized, mixed fluvial-tidal estuarine succession that disconformably overlies the Lower McMurray fluvial deposits. The channelized portion of the Upper McMurray estuarine succession is generally comprised of a fining-upward sedimentary package with clean blocky sands at the base overlain by interbedded sands and mudstones that become increasingly argillaceous upsection. Channel sands grade upward into inclined heterolithic stratified units of rippled sand/heavily burrowed silty mudstones (laterally accreting deposits). The lateral accretion deposits are overlain by moderate to intensely burrowed mixed sand and mudstone reflecting channel abandonment phases (vertical accretion deposits) or overbank successions. Mudstone intraclast breccias are common within the sand-dominated portions of the channel successions. Interfluves, between channels, received more horizontally bedded, rare to intensely burrowed, variably mixed sand-mudstone lithologies (tidal flat deposits) with some thin successions displaying distinct coarsening upward profiles (crevasse splay deposits).

The scale and style of channelization within the Upper McMurray varies considerably throughout the Athabasca Oil Sands deposit. Channel size within the McMurray succession varies significantly within the oil sands deposit from thick, large single event channels to smaller scale multi-event channel complexes. Stacked channels at both scales are common. Subsurface gamma ray profiles over the Upper McMurray often display up to three stacked fining upward successions. Channel preservation is dependent upon the degree of incision of the successively younger channel events. Channel stacking can be best verified using core, especially when eroded lateral accretion and less commonly vertical accretion deposits are partially preserved within older channel successions. In general, larger scale channels (> 10 m deep) tend to be situated near the base of the Upper McMurray succession, with the smaller scale channel-fills (< 10 m deep) preserved higher in the section. Large channel-fills tend to be sand-dominated, whereas smaller channels range from sand- to mudstone-dominant. Exceptions exist, particularly along trend with the linear Prairie Salt Scarp where thick channel sediments have been observed near the top of the Upper McMurray. Here structural collapse of the sedimentary succession along the salt scarp redirected localized channel trends by affecting depositional gradients along the linear depression. This resulted in both north-south and east-west trending channel orientations, with infill of a distinctive, dominantly sandy, succession near the top of the McMurray Formation.

Fossil preservation within the McMurray Formation is rare, with the exception of very localized gastropod and rare pelycypod accumulations ranging from scattered, intact shells within a sandy or muddy matrix to concentrated hashes comprised of densely packed shell fragments. Microfossils, including pollen, spores and dinoflaggelates, are locally abundant within mudstone dominated successions (Appendix 4). In contrast, trace fossils are very prevalent within the Upper McMurray succession and are a prominent factor in the facies classification scheme. The variably argillaceous interbedded sand, siltstone and mudstone display bioturbation textures ranging from rare to churned (no preserved primary stratification), often increasing in intensity and diversity upsection. Dominant trace fossils include *Planolites* and *Cylindrichnus*, less commonly *Skolithos*, *Teichichnus*, and *Gyrolithes*. Rooting is relatively rare and is most commonly found within the uppermost Upper McMurray sediments (Appendix 5).

Coastal plain sediments that typically would cap portions the Upper McMurray succession are, for the most part, believed to have been eroded by the erosion surface that separates the McMurray Formation from the overlying Wabiskaw Member (Clearwater Formation). Significant relief on the unconformity surface, particularly in the northern regions of the oil sands deposit (seaward end), has likely removed most of the coastal plain succession. Discontinuous remnants of the coastal plain deposits are present on the Ells and Steepbank rivers. Recent work along the downstream end of the Ells River, north of Fort Mackay, has documented the occurrence of thin, laterally extensive, horizontal coal seams and wave rippled units, along with very small scale (< 0.5 m wide x < 0.25 m deep) scours cut into the top of coastal plain sediments. Such associations may indicate a low gradient drainage network across which tides receded, creating sheets of wave-rippled sand and runnel-networks.

Lithologically the Upper McMurray comprises micaceous, fine- to medium-grained sand, silt and clay, with rare siderite as cement and intraclasts, and pyrite nodules up to 10 cm in diameter. Autochthonous coal seams are interbedded with brackish bay silty clay, with allochthonous reworked organic debris now preserved as mummified logs, and organic carbon detritus now preserved as lignite and comminuted carbon in the channel and washover sands. Accessory heavy minerals include tourmaline, zircon and chloritoid, with clay minerals kaolinite and illite (Carrigy, 1959a,b, 1962, 1963a, b, 1966, 1967; Mellon, 1955, 1956). The local occurrence of siderite, calcite and pyrite cements is less common than in the underlying Lower McMurray succession.

4.3.3. Upper Contact -McMurray Formation/Wabiskaw Member of the Clearwater Formation

The topmost unconformity separating the McMurray succession from the overlying Wabiskaw Member has relief on the order of 5 to 10 metres, with localized downcutting up to 35 metres. Picking the upper erosional contact with the overlying Wabiskaw Member can be problematic from geophysical logs, particularly where both successions are commonly dominated by mudstone. However, lithologic characteristics and sedimentary facies are markedly different above and below the McMurray/Wabiskaw contact, so core must often be viewed to confirm the erosional boundary.

The uppermost portion of the McMurray succession consists of brackish coastal plain deposits or interfluve overbank deposits, depending upon the location. Strata generally lack beach laminations, wave-formed structures, and have a restricted, diminished size trace- fossil assemblage. By contrast, the Wabiskaw Member represents a nearshore-marine succession, with lithic, sandy mudstones and sand units (Figure 14, 15), a pronounced increase in the diversity and size of trace fossils (Figure 15), a change from more brackish trace fossils assemblages (*Skolithos, Cylindrichnus* and *Planolites*) to more marine trace fossil assemblages (*Asterosoma, Teichichnus, Thalassinoides,* and *Rhizocorrallium*); and, the prominence of glauconite. The underlying McMurray sediments are often mudstone-dominated, with colours ranging from buff, tan-grey to medium grey. By contrast, finer interbeds in the lower part of the Wabiskaw Member have a dark, steel blue grey or black colouration. Palynological analyses of mudstones below and above the McMurray/ Wabiskaw contact confirms a change in environments from brackish to fully marine; and a significant difference in ages (Appendix 4).

Traditionally the base of the Wabiskaw Member was identified by the presence of glauconite (Badgley, 1952), and strata directly underlying the glauconite-rich horizon was included as part of the McMurray succession. Detailed stratigraphic work of the last several years suggest the base of the Wabiskaw Member is lower, especially when there is a thick Wabiskaw valley-fill succession (i.e. range of 1 to 30 m lower). Thus, in the past, some marine units that should have been mapped as Wabiskaw Member have been mistakenly assigned to the Upper McMurray Formation (Wightman *et al.*, 1995).

The nature of the upper bounding surface separating McMurray sediments from the overlying Wabiskaw Member is sharp and erosional. Topographic relief along the upper bounding surface is typically much less than that of the basal unconformity (est. 5 to 10 m), but may be more complex than the basal unconformity in that the upper contact is one of two unconformity surfaces. (Lower Surface E10 and Upper Surface T10.5 of Wynne *et al.*, 1994; Wightman *et al.*, 1995; Appendix 2). The lower erosional surface (Surface E10) reflects a short-lived relative sea level drop and the upper erosion surface (Surface T10.5) reflects the ensuing transgressive event. In regions where erosion on the lower E10 surface is minimal (e.g. < 3 m) the overlying disconformity surface T10.5 may incise below the E10. In this case T10.5 marks the

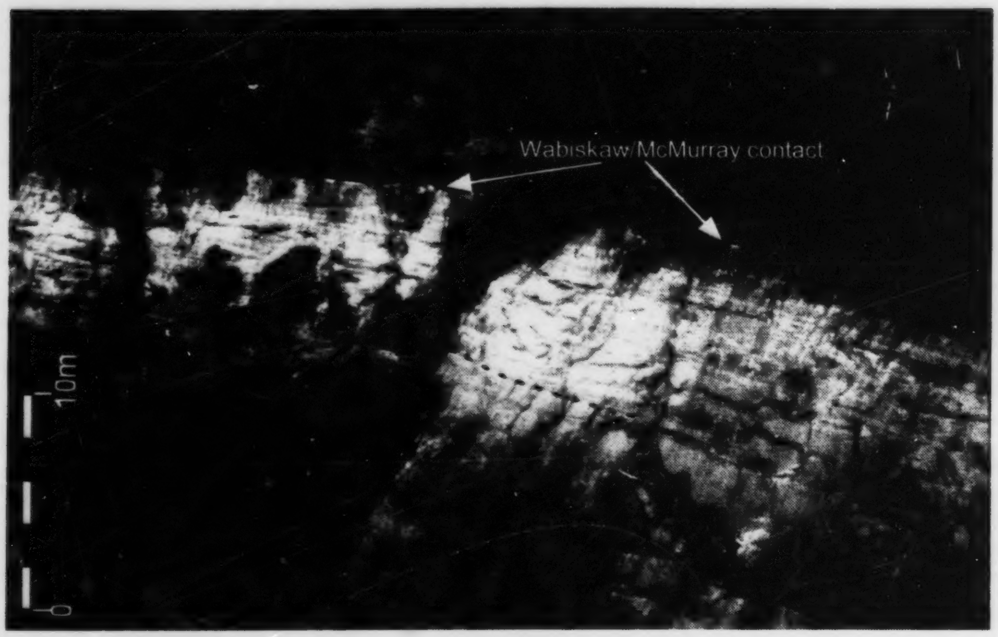
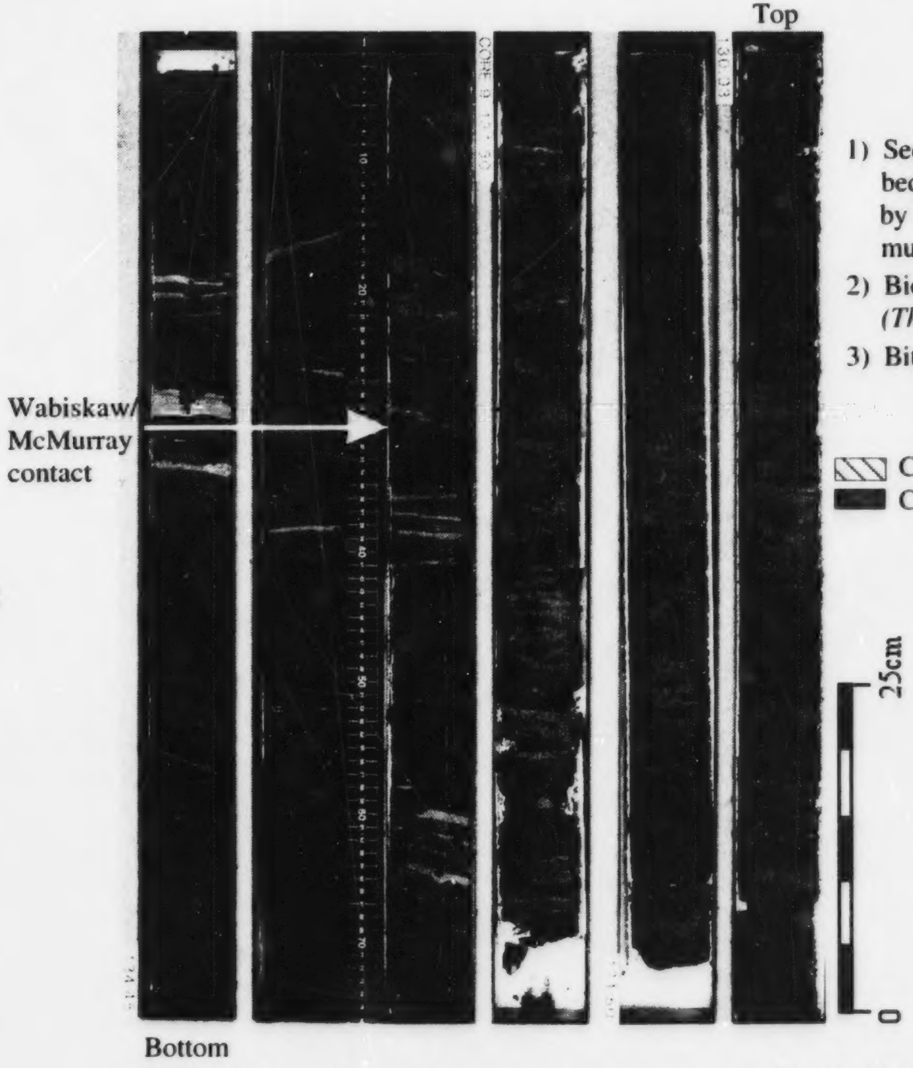


Figure 14: Clean white, cross bedded sand (preserved transgressive shoreface deposit) of the Upper McMurray Formation abruptly overlying bitumen-bearing estuarine sands of the Upper McMurray Formation. Outcrop along the Horse River. Possible paleo-gas/bitumen contact indicated by dashed line.


Top
130.03
CORE 9 131.50
Wabiskaw/
McMurray
contact
25cm
0
Bottom

1) Sedimentary Features: medium bedded sand unconformably overlain by burrowed, wavy bedded sandy mudstone
2) Bioturbation Index: 2-3 *(Thalassinoides)*
3) Bitumen Saturation: poor

▨ Cored Interval
■ Core Interval Viewed

AO-58
AD/15-07-093-12W4
G.L. 431.34m

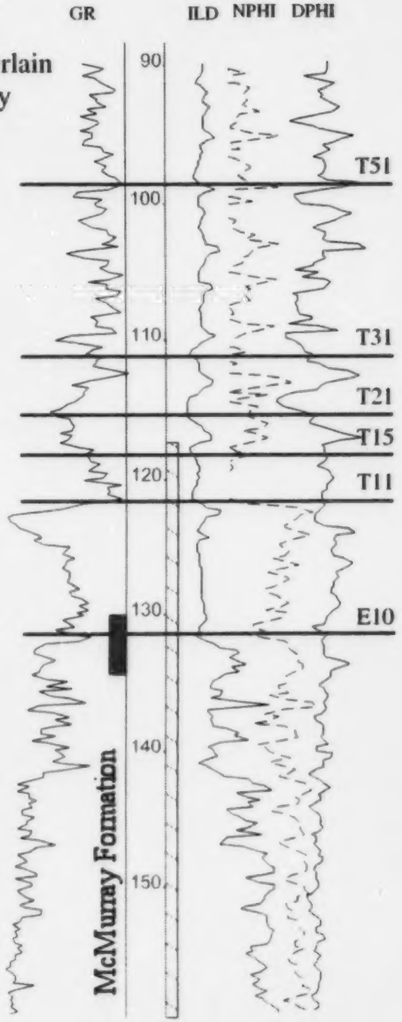


Figure 15: Greenish-grey, burrowed, sandy mudstone of the Wabiskaw Member, Clearwater Formation, unconformably overlying bitumen-bearing estuarine sands of the Upper McMurray Formation. Arrow on core photograph indicates the unconformity surface. Geophysical log responce shown to the right.

Wabiskaw/McMurray contact. The lower erosion surface (Surface E10) has relief of over 30 m in isolated regions, the most prominent area located north of the former AOSTRA Underground Test Facility (UTF). Ongoing mapping and facies analysis of the Wabiskaw Member indicates that the extensive incised, transgressive valley-fill succession, comprising the Wabiskaw-D valley-fill (Figure 16), was emplaced above the McMurray Formation following a significant erosional event (Surface E10). The upper erosion surface (surface T10.5) marks a major transgressive surface of erosion that advanced across the Athabasca region, succeeded by the deposition of the coarsening-upwards, sandy marine glauconitic mudstone (Figure 17) and glauconitic sandstone (Figure 18) components of the Wabiskaw-C unit (see next section).

A structure map of the top of the McMurray Formation (Figure 7) shows a deepening to the north-northeast along the Prairie Salt Scarp and into the Bitumount Basin (Figures 6, 7). Minor topographic relief at the top of the McMurray succession is preserved in the southeastern part of the regional study area, and along the present valley of the Athabasca River (Figure 7). At present, it is not known if these highs and lows reflect true paleotopographic relief, possible reactivation along basement faults, or if they merely represent an apparent topography, that is a consequence of the line of section or data distribution.

4.3.4 Clearwater Formation

The base of the Clearwater Formation unconformably/disconformably overlies the McMurray Formation. Two well-defined units occur along the base of the Wabiskaw Member: a lowermost dark steel-blue grey marine/estuarine wavy-bedded muddy sand to sandy mudstone, the Wabiskaw D; and an upper, marine glauconitic green sand, the Wabiskaw C. The basal erosional surface, as discussed above, may be near-horizontal (with relief of about 5 m over a broad area) or quite pronounced, with negative relief up to 30 metres, where incised Wabiskaw-D valley-fills have cut deeply into the underlying McMurray Formation (Wightman *et al.*, 1995).

The basal Wabiskaw-D succession is generally comprised of thin to medium interbedded sand and mudstone. The mudstone laminae/beds are distinctly steely bluish grey and are often wavy bedded. Where the unit is thick (>5 m) the succession is generally sand-dominated; where thin, the succession is most often mudstone-dominated. Trace fossils include robust forms of *Asterosoma, Thalassenoides, Paleophycus* and *Planolites*. On the gamma-ray log the succession often displays a distinct coarsening-upward profile. The Wabiskaw-D is disconformably overlain by the Wabiskaw-C succession that consists of glauconitic, salt and pepper lithic sand (Figures 16 – 18) (cf. Wightman *et. al.*, 1995). The Wabiskaw-C sand rarely exceeds 3 metres thick in the study area and typically displays a coarsening-upward profile on the gamma-ray log. *Thalassinoides, Diplocraterion,* and *Aestrosoma* burrows are common within the unit. A transgressive lag consisting of poorly sorted, medium- to coarse-grained sand often marks theWabiskaw D/C surface, but is not definitive.

In general, the Wabiskaw Member was deposited within an overall transgressive cycle, with short-lived progradational regressive pulses recorded by thin coarsening-upward sands (Cant, 1998). Locally, at the western edge of the study area, thicker coarsening-upward sands occur against local paleohighs on the pre-Cretaceous unconformity, forming thick stacked shoreline

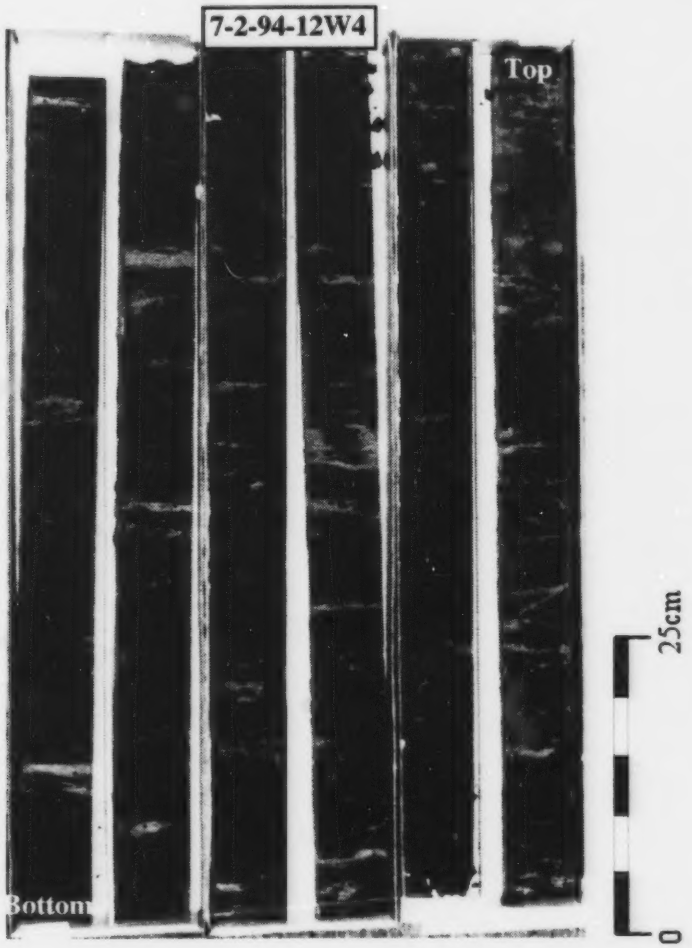
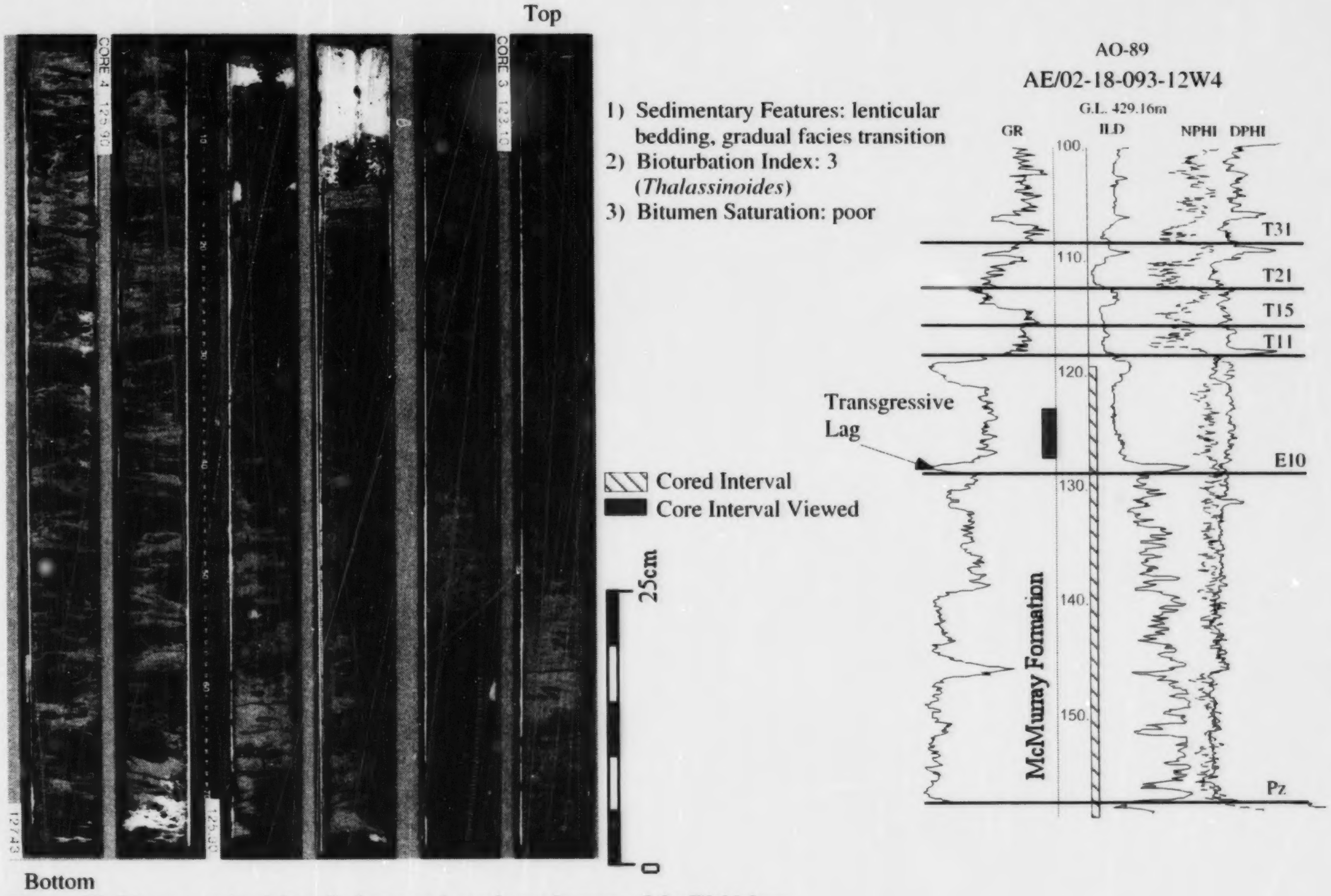

7-2-94-12W4
Top
Bottom
25cm
0

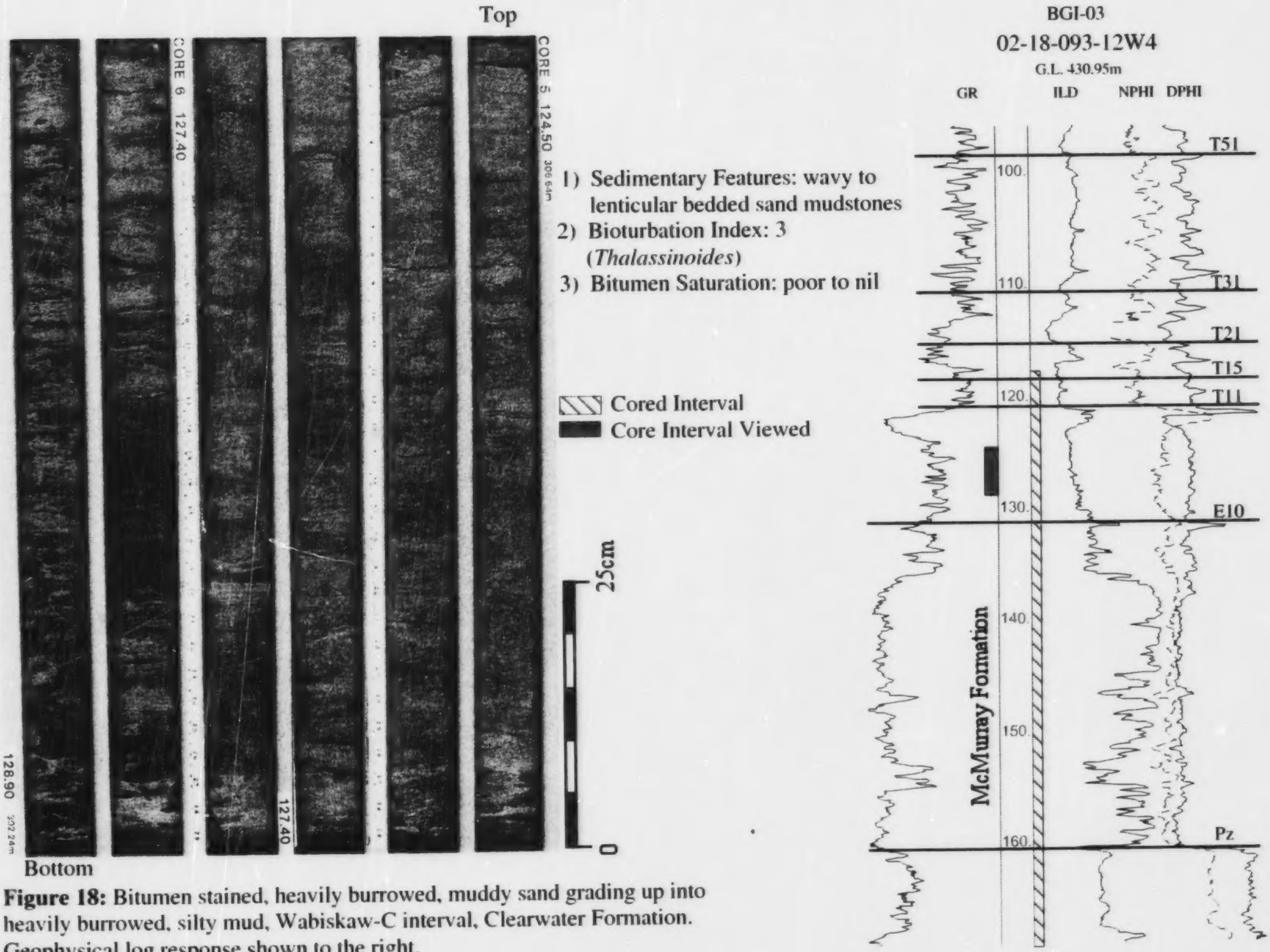
Figure 16: Bitumen stained, burrowed, estuarine muddy sand of the Wabiskaw succession, valley fill (D interval), Wabiskaw Member, Clearwater Formation.


Top
CORE 3 123.10
CORE 4 125.90
125.90
127.43
Bottom
25cm
0
AO-89
AE/02-18-093-12W4
G.L. 429.16m
GR
ILD
NPHI
DPHI
100
110
120
130
140
150
T31
T21
T15
T11
E10
Pz
Transgressive Lag
McMurray Formation

1) Sedimentary Features: lenticular bedding, gradual facies transition
2) Bioturbation Index: 3 (*Thalassinoides*)
3) Bitumen Saturation: poor

▨ Cored Interval
■ Core Interval Viewed

Figure 17: Bitumen stained, heavily burrowed, sandy mudstones of the Wabiskaw Member (C interval). Geophysical log response shown to the right.



Top
CORE 5 124.50 306.64m
CORE 6 127.40
127.40
128.90 302.24m
Bottom
25cm
0
BGI-03
02-18-093-12W4
G.L. 430.95m
GR
ILD
NPHI
DPHI
T51
T31
T21
T15
T11
E10
Pz
100
110
120
130
140
150
160
McMurray Formation

1) Sedimentary Features: wavy to lenticular bedded sand mudstones
2) Bioturbation Index: 3 (*Thalassinoides*)
3) Bitumen Saturation: poor to nil

▨ Cored Interval
■ Core Interval Viewed

Figure 18: Bitumen stained, heavily burrowed, muddy sand grading up into heavily burrowed, silty mud, Wabiskaw-C interval, Clearwater Formation. Geophysical log response shown to the right.

successions. Several gas accumulations are hosted within these shoreline sands. From a regulatory viewpoint, they are upper sands within the Wabiskaw-McMurray deposit. However, from a geologic viewpoint, they are not part of the McMurray Formation, but rather the Clearwater Formation, and are separated from the underlying McMurray bitumen-bearing sands by a significant unconformity.

The top of the Wabiskaw C is overlain by the first regional marine shale (surface T11 of Wynne *et al.*, 1994; Wightman *et al.*, 1995; Appendix 2). Overlying the first regional marine shale are two other sands within the Wabiskaw Member – the Wabiskaw A and Wabiskaw B. The top of each are marked by transgressive transitions back into the regional marine shale (surfaces T15 and T21 of Wynne *et al.*, 1994; Wightman *et al.*, 1995; Appendix 2). The top of the Wabiskaw Member is defined by the 'Wabiskaw Marker,' (surface T21 of Wynne *et al.*, 1994; Wightman *et al.*, 1995; Appendix 2) a regional mudstone, with a distinctive log-signature, and is used as a stratigraphic datum throughout most of the Athabasca deposit (Figure 5). Mudstone, siltstone and thin sandstone conformably overlie the 'Wabiskaw Marker.' The Wabiskaw Marker is interpreted to represent a condensed section that separates the McMurray-Wabiskaw interval from overlying regional marine shales of the Clearwater Formation (Wightman *et al.* 1995). Marine mudstone and siltstone dominate the regional marine shales of the Clearwater Formation, with local coarsening-upward cycles capped by thin sandstone. The Clearwater succession within the study area is marine, a deeper water, basinal equivalent to thick shoreline successions located south of the present study area.

4.4 Regional Depositional Trends of the McMurray Formation

Overall the McMurray succession is sand-dominated in many parts of the study area, although locally thick muddy intervals are present. Deposits become finer grained and muddier upsection. From south to north the succession reflects a change from fluvial to brackish estuarine to marginal marine environments. Most bitumen reservoirs occur within channel sands of the Lower McMurray fluvial and Upper McMurray mixed fluvial-estuarine/coastal plain succession. The thickest McMurray deposits are located within a large, northwest-trending linear depression known as the Prairie Salt Scarp. Isopach and structure maps of the McMurray Formation indicate that this collapse was both syn-and post-depositional, with active dissolution occurring up to the present (i.e. La Saline Lake deposits, Athabasca River valley).

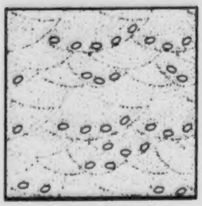
During McMurray time, tributary paleodrainages entered the main salt-scarp valley system, locally supplying siliciclastic detritus. These tributary paleodrainages merged with the main fluvial and estuarine drainage systems during Lower and Upper McMurray time. The drainage network narrowed to the northwest through a constriction, and then broadened into the Bitumount Basin. At the end of McMurray time, a drop in relative sea level resulted in erosion of most of the topmost coastal-plain and shoreline sediments. With the ensuing transgression, more marine units of the Clearwater Formation were emplaced unconformably over the preserved McMurray succession.

5.0 LITHOFACIES DESCRIPTION AND INTERPRETATION

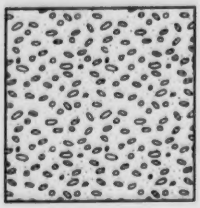
The facies classification of the McMurray Formation presented in this report attempts to categorize and describe individual facies in an orderly a fashion. In general, facies are discussed in the order in which each facies was deposited. Facies of the Lower McMurray succession are introduced first, followed by facies of the Upper McMurray. Of course this method can not be rigorously adhered to because some of the facies described are present within both successions. As well, similar facies or facies which are gradational from one facies to another are grouped together into subfacies.

A summary chart of the lithofacies classification scheme is presented in Figure 19. In the following section a brief description is given of each lithofacies along with an interpretation. For each facies (or subfacies) description there is a composite figure illustrating typical core and/or outcrop photographs, and in most cases representative geophysical log signatures.

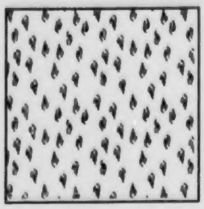
Facies 1: Coarse Grained to Pebbly, Poorly Sorted, Trough Cross Bedded Sand



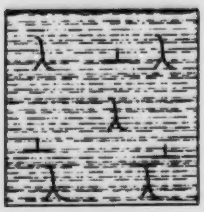
Facies 2: Very fine Grained to Pebbly, Poorly Sorted, Graded Gravel



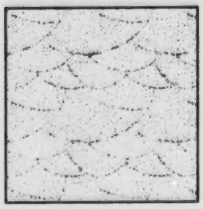
Facies 3: Carbonaceous to Coaly, Rooted Silty Mudstone



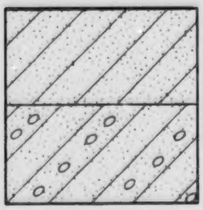
Facies 4: Mottled Argillaceous Sandy Marl



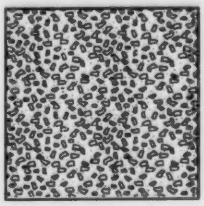
Facies 5: Fine to Medium Grained, Trough Cross Bedded Sand



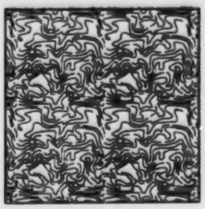
Facies 6: Fine Grained to Pebbly, Planar-Tabular Cross Bedded Sand



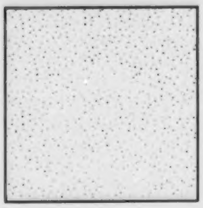
Facies 7A: Fine to Medium Grained, Poorly Sorted, Mudstone-Clast Breccia



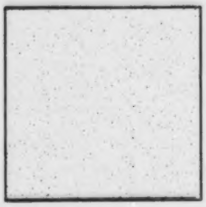
Facies 7B: Slumped Sand and Mudstone



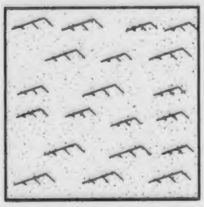
Facies 8A: Fine to Coarse Grained, Massive Sand



Facies 8B: Poorly to Well Sorted, Massive Sandy Silt/Silty Sand



Facies 9A: Very Fine to Fine Grained, Ripple Cross Bedded Sand



Facies 9B: Very Fine to Fine Grained, Flaser Bedded Sand and Mudstone

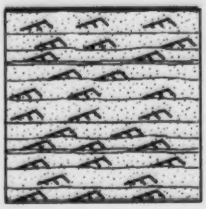
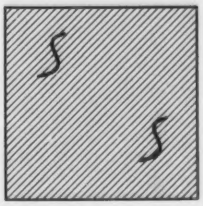
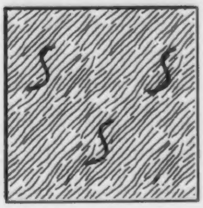


Figure 19: Facies classification and scheme with sketch illustrating the dominant sedimentary features

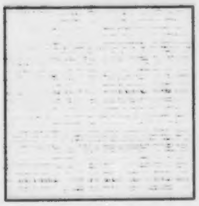
Facies 10A: Bioturbated, Inclined Heterolithic Stratified Muddy Sand



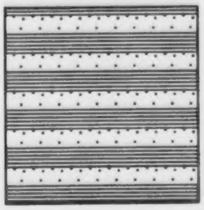
Facies 10B: Bioturbated, Inclined Heterolithic Stratified Sandy Mudstone



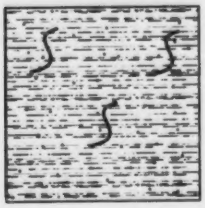
Facies 11: Very Fine to Medium Grained, Stratified Sand



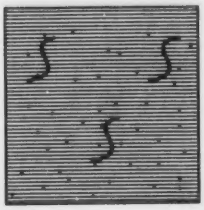
Facies 12A: Rhythmically Laminated Sand and Mudstone



Facies 12B: Very Fine to Fine Grained, Bioturbated, Muddy Sand



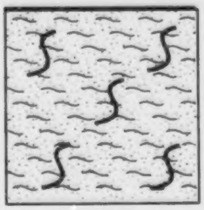
Facies 12C: Very Fine to Fine Grained, Bioturbated, Sandy Mudstone



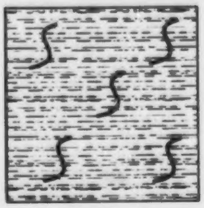
Facies 12D: Laminated to Thinly Interbedded, Bioturbated Silty mudstone

Facies 12E: Thinly Laminated Silty Mudstone/Mudstone

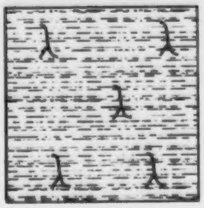
Facies 13A: Very Fine Grained, Heavily Burrowed Muddy Sand



Facies 13B: Intensely Burrowed, Silty Mudstone/Muddy Silt



Facies 14: Coaly and/or Rooted, Sandy-Muddy Siltstone to Silty Mudstone



Facies 15: Coarsening-Upward Mudstone-Siltstone-Sand

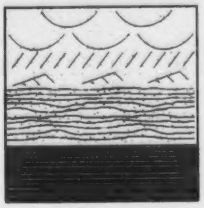
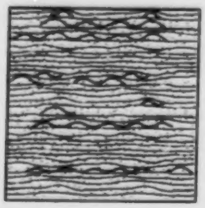
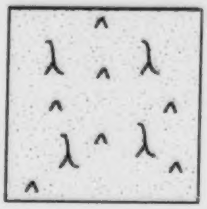


Figure 19: Facies classification and scheme with sketch illustrating the dominant sedimentary features

Facies 16: Very Fine to Fine Grained, Well Sorted, Wave Rippled Sand



Facies 17: Silicified Sandstone ('Beaver River Sandstone')



Facies 18: Poorly Sorted, Karstic Calci-/Siliciclastics

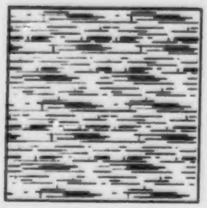


Figure 19: Facies classification and scheme with sketch illustrating the dominant sedimentary features

5.1 Facies 1: Coarse Grained to Pebbly, Poorly Sorted, Trough Cross Bedded Sand

Facies 1 is generally confined to the lowermost portion of the McMurray succession, often directly overlying the sub-Cretaceous unconformity. Facies 1 is common in the Lower McMurray, and is rare within the Upper McMurray. Coarse-grained to pebbly, trough cross-bedded, quartz-dominated sand characterizes the unit (Figure 20, 21, 22). Beds average about 0.75 metre thick, with amalgamated beds stacking up to 9 metres thick in outcrop exposures. Trough cross bed sets generally range from 0.5 to 1.0 m in height and may extend 1 to 3 m laterally and have an erosional top and base. Granules and pebbles commonly occur as thin laminae along cross bedding foresets or occur as lag deposits at the base of individual bedsets. The sand is subangular to subrounded and is most often poorly sorted. Facies 1 is variably argillaceous ranging from very clean (with no clay) to moderately argillaceous. Abundant sideritic mudstone clasts (10 to 15 cm in diameter) have been observed. The unit sometimes contains thin, discontinuous beds of light grey, silty mudstone that separate cross bed sets. Very thin, discontinuous lenses of coaly debris are observed in rare to moderate amounts.

Facies 1 is most commonly found as relatively thin, scattered, discontinuous pods overlying the sub-Cretaceous unconformity along the main valley trend and associated deeply incised tributaries. The unit becomes progressively thicker and somewhat more continuous to the north where the main valley intersects the Bitumount Basin. Thin occurrences of this facies are sometimes preserved outside, but proximal, to the main valley system. The unit is often associated with relatively thick, light grey, carbonaceous mudstones (Facies 3), massive sand (Facies 8A), mudstone clast breccias (Facies 7A), pebbly, high angle, planar tabular cross bedded sand (Facies 6), and slumped sediments (Facies 7B). On the gamma-ray log traces the facies typically appears as a very clean, blocky sand that overlies, is interbedded with or is capped with relatively thick mudstone (Figure 21).

The coarse grained, trough cross-bedded facies has been observed at outcrops along the Athabasca, Steepbank, and MacKay rivers. The unit is usually poorly exposed and is limited in both vertical and lateral extent (vertical succession < 5 metres). In core, Facies 1 is recognized by the coarse grained to pebbly, poorly sorted nature of the unit and the directional switching of high to low angle cross bedding (Figure 21).

Interpretation: This facies is interpreted as being deposited from three-dimensional coarse grained to pebbly sand dunes that migrated along the bottoms of river channels, or less commonly, formed the deeper portions of coarse grained braid bars or flat complexes. Braided rivers flowed within confined valleys, which resulted in complex facies associations, both vertically and laterally. Later, these fluvial deposits were often modified or totally removed and reworked into the overlying transgressive estuarine system. Isolated, intact remnants of these coarse grained fluvial lowstand deposits are preserved in lows along the unconformity surface, as 'inliers' surrounded by Upper McMurray estuarine deposits, or as 'outliers' on isolated pre-Cretaceous bedrock highs that were flooded during Lower McMurray time. Facies 1 is interpreted as one of the dominant facies of the initial fluvial lowstand system that occupied the poorly organized drainage network on the pre-Cretaceous unconformity surface.

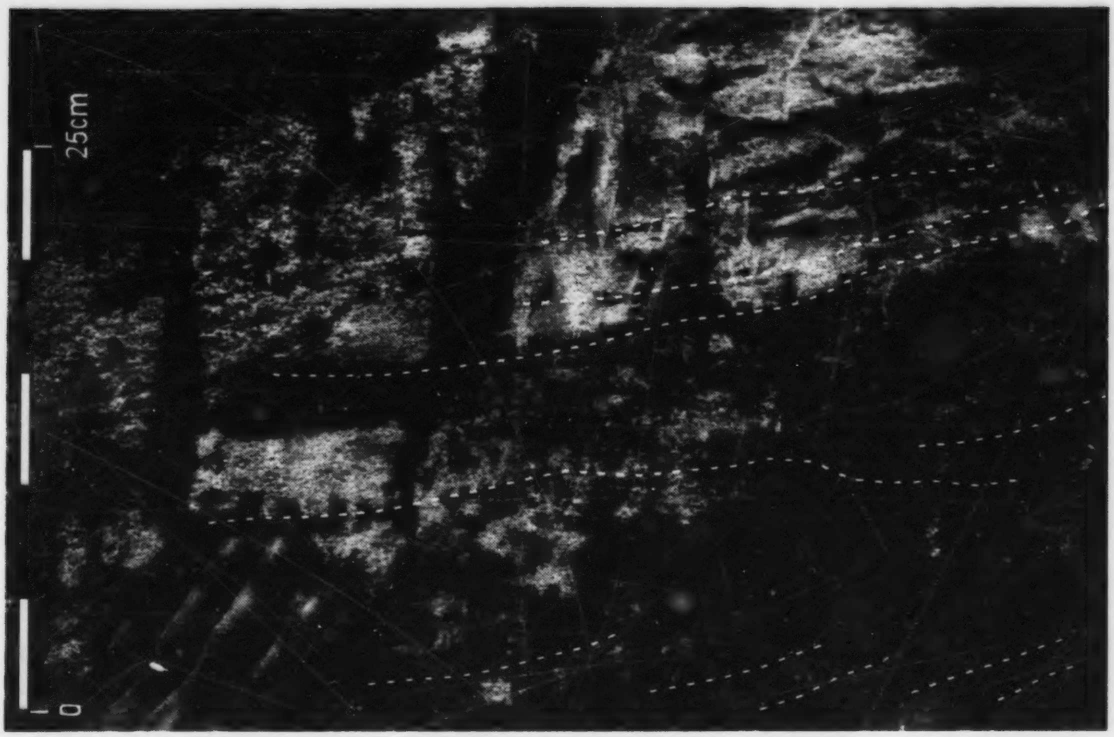
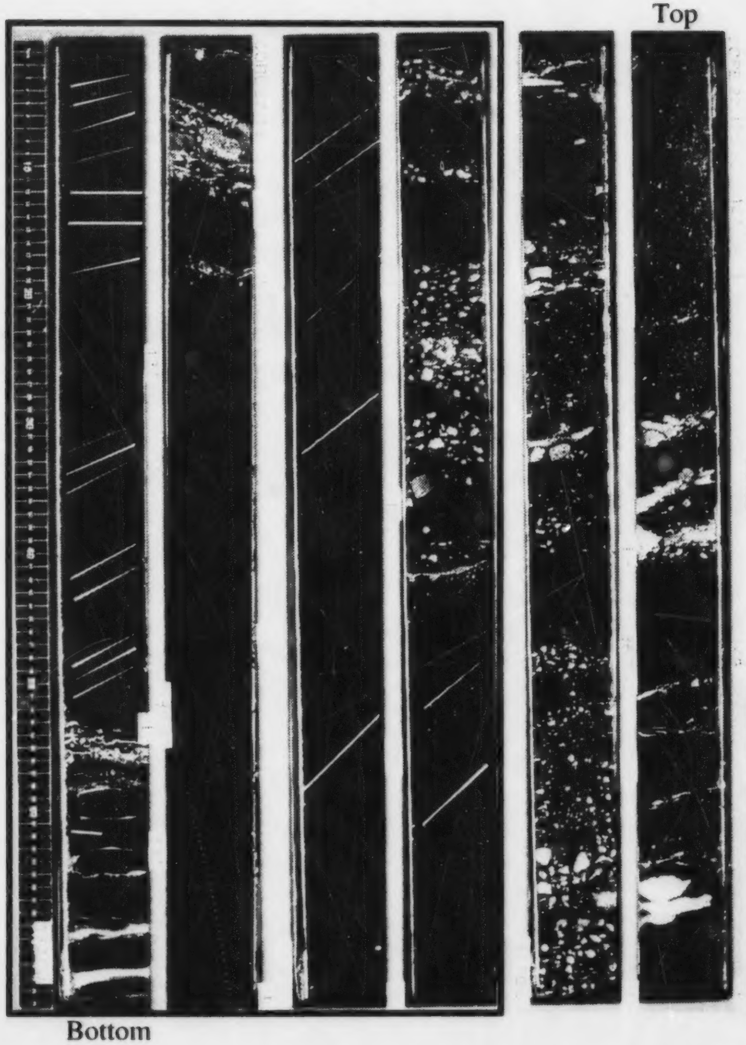


Figure 20: Coarse-grained, small-scale trough cross-beds in poorly saturated, bitumen stained, sand, Lower McMurray Formation, Outcrop #4-1, Steepbank River. Facies 1.



1) Sedimentary Features: trough cross beds
2) Bioturbation Index: 0
3) Bitumen Saturation: good

▨ Cored Interval
■ Core Interval Viewed

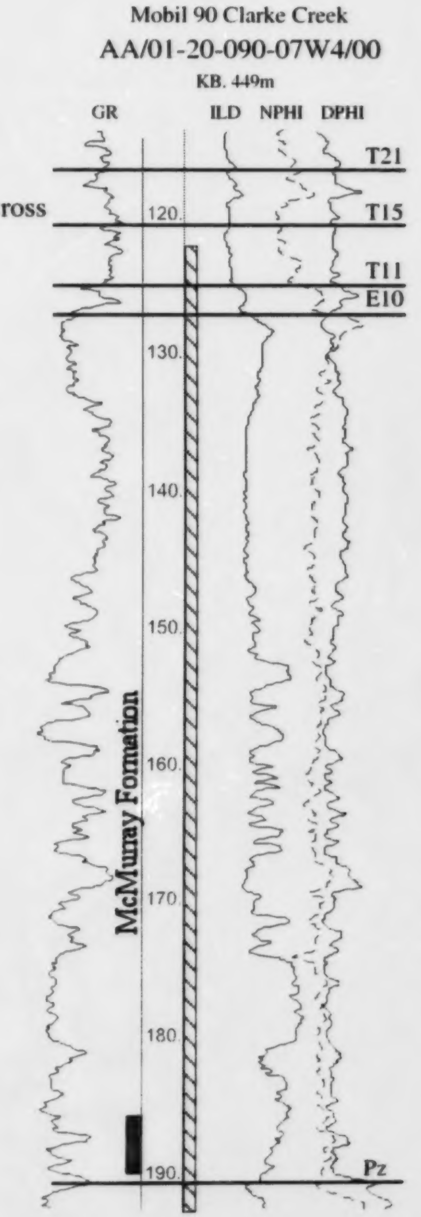


Figure 21: Bitumen stained, trough cross bedded, coarse to pebbly sand with scattered mudstone intraclasts. (highlighted portion). Facies 1. Geophysical log response shown to the right.

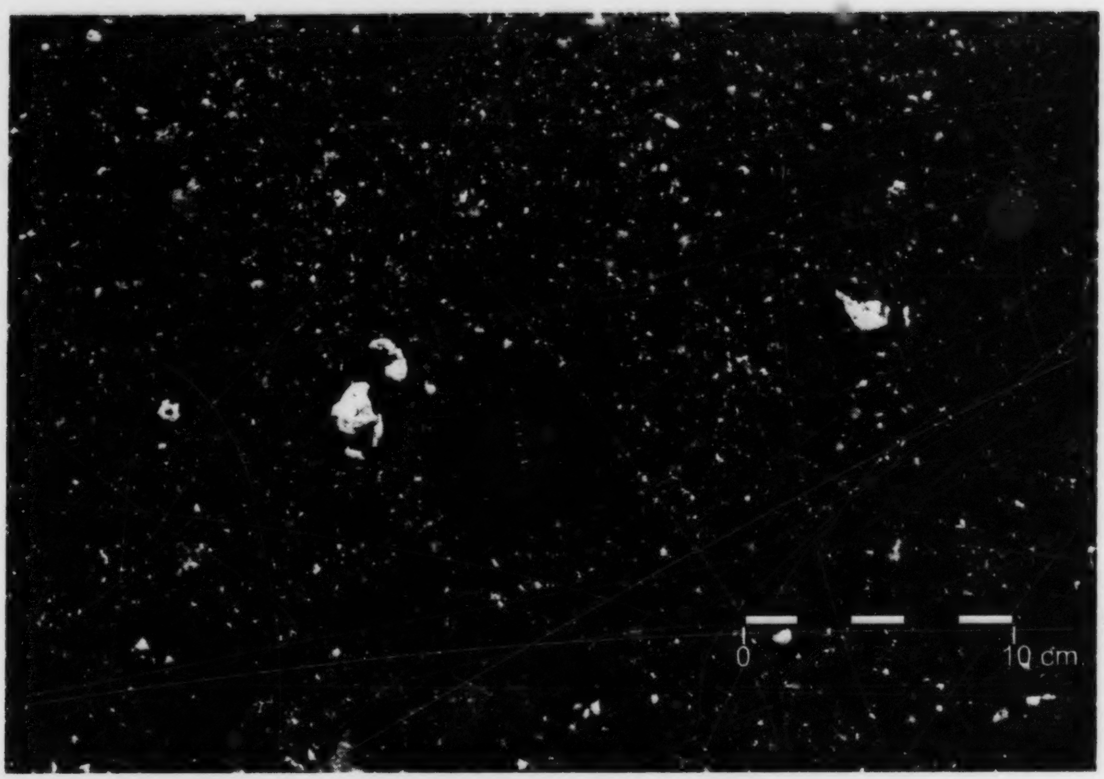


Figure 22a: Poorly sorted, coarse to granular grained, argillaceous, trough cross-bedded sand, interpreted as a fluvial deposit within the Lower McMurray Formation. Larger, white clay clasts (some sideritized) are common. Outcrop on the Athabasca River just upstream of Tar Island (Suncor), north of Fort McMurray. Facies 1.

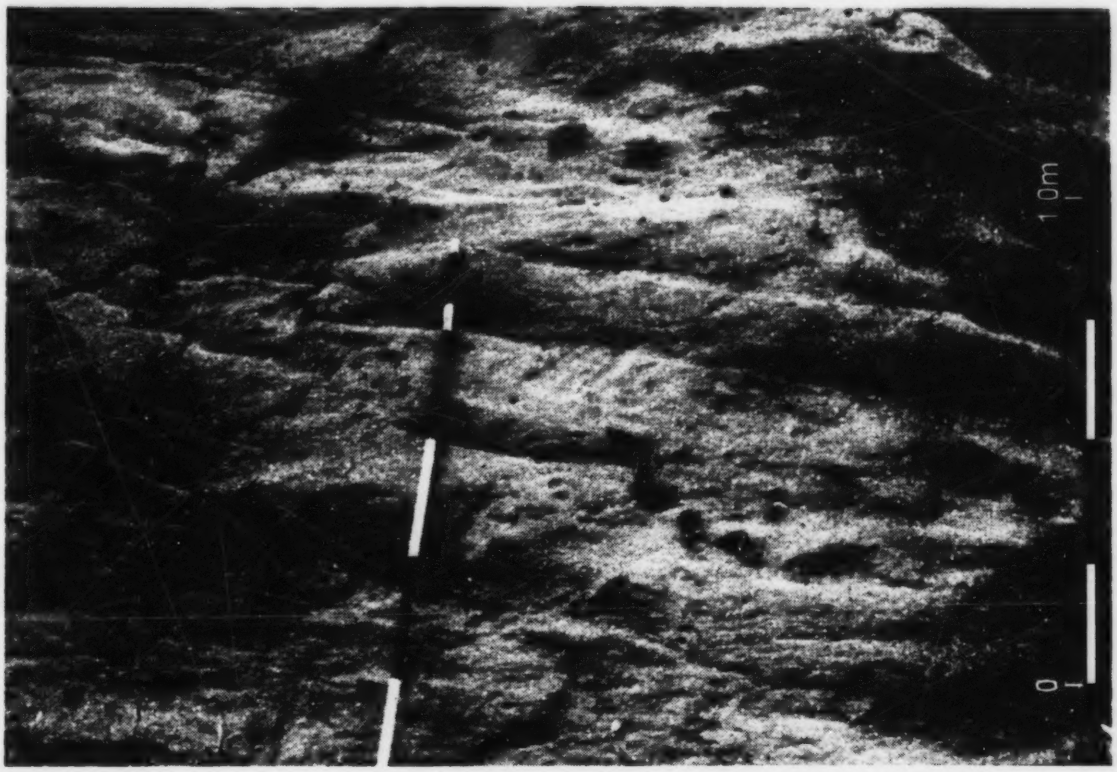


Figure 22b: Trough cross-bedded, coarse grained sand with siderite clasts, Lower McMurray along the Athabasca River, upstream from Tar Island, south of Suncor plant. Facies 1.

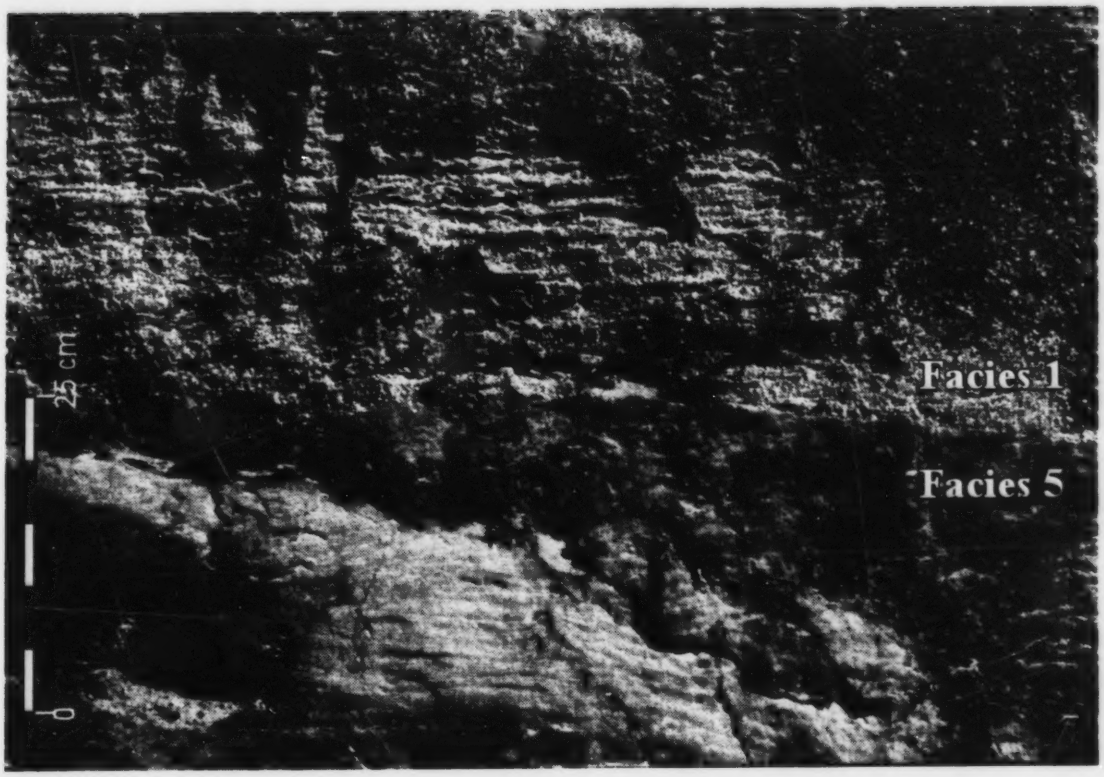


Figure 22c: Coarse grained, trough cross-bedded sand (laterally discontinuous cut and fill), unconformably overlying fine grained, trough cross-bedded sand, Athabasca River type section of the McMurray Formation, north of Fort McMurray (Upper McMurray). Facies 1, 5.

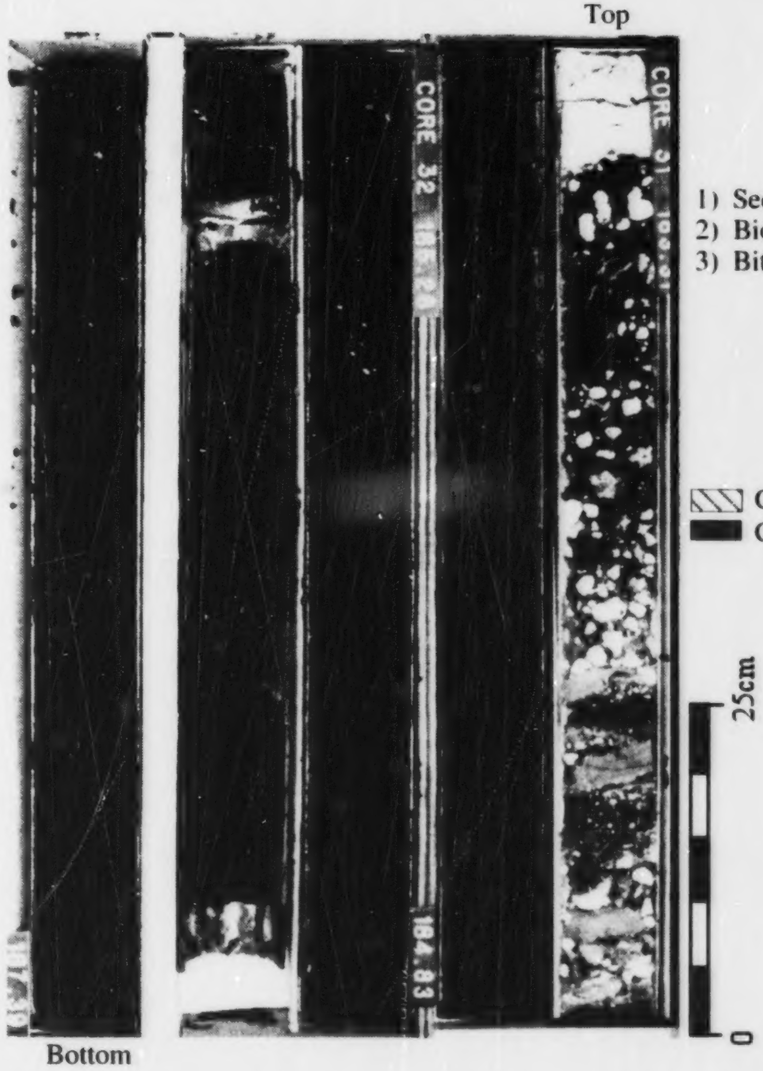
5.2 Facies 2: Very Fine Grained to Pebbly, Poorly Sorted, Graded Gravel

Facies 2 is a relatively uncommon facies in the Lower McMurray Formation. The characteristic feature of this facies is the occurrence of clast- or matrix-supported, poorly sorted gravel that is massive (Figure 23a) or shows inverse or normal grading (Figures 23b and 23c). Graded gravels average 0.75 metres thick, ranging in thickness from about 0.25 metres to 1.0 metres. Less commonly carbonaceous material, including coalified or mummified logs are in the graded gravel beds.

Facies 2 is most commonly found within the Lower McMurray succession situated along the main north-south valley trend (Prairie Salt Scarp) and associated tributaries. Although not well documented, this gravelly facies appears to be more prevalent in the northern region. Facies 2 is often associated with the other sands/pebbly sands (Facies 1, 6, 9A), sand-siltstone/mudstone (7B, 15, 12A), and slump deposits (Facies 7B). The gravelly facies often directly overlies the pre-Cretaceous unconformity or is bound below and above by carbonaceous mudstones (Facies 3). The deepest parts of the main valley trend often contain thick water saturated sand comprised of poorly-sorted, coarse to pebbly sand.

Facies 2 has been observed on the Athabasca, MacKay and Ells rivers. As previously mentioned, the gravelly facies is often found overlying the pre-Cretaceous unconformity. In core Facies 2 is recognized by the well-developed variable grading patterns within the gravel units. One of the more common occurrences of this facies is along the contact between the Lower and Upper McMurray Formations, perhaps indicative of a rapid transgressive flooding event along the disconformity that separates the fluvial lowstand deposits of the Lower McMurray from the overlying transgressive estuarine deposits of the Upper McMurray. This contact, in some instances, is difficult to pick because the gravelly Lower McMurray facies has been partially or totally reworked into the overlying Upper McMurray Formation during transgressive erosional events.

Interpretation: This facies is interpreted as being deposited from sediment gravity flows that mobilized existing gravel deposits and resedimented them locally within the depositional setting. Such remobilization was common along areas of significant paleotopographic relief, such as along steep channel margins that were incising into underlying sediment, or as local material resedimented from bedrock highs into the surrounding fluvial and estuarine channel systems. The graded, matrix-supported gravel sediment may have originated from debris flows; whereas the graded, clast-supported gravel may have resulted from deposition from hyperconcentrated flood flows or grain flows. High-energy flood events could also trigger sediment gravity flows. This facies is interpreted as a relatively uncommon component of the fluvially dominated lowstand deposits. The facies also represents the transgressive lag separating the Lower and Upper McMurray successions.


Top
CORE 31
CORE 32
184.83
Bottom
25cm
0

1) Sedimentary Features: poorly sorted
2) Bioturbation Index: 0
3) Bitumen Saturation: poor

▨ Cored Interval
■ Core Interval Viewed

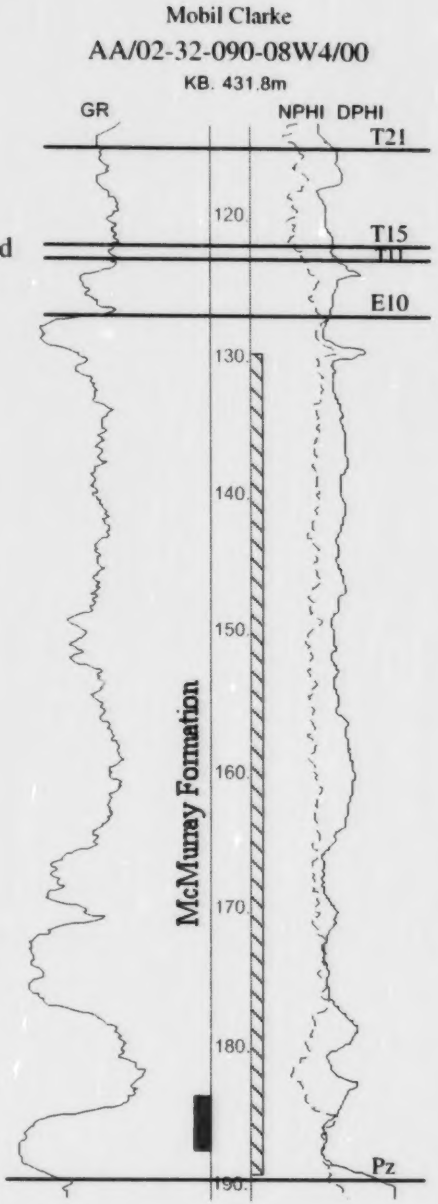


Figure 23a: Bitumen stained, matrix- and clast-supported gravel (highlighted portion). Facies 2. Geophysical log response shown to the right.

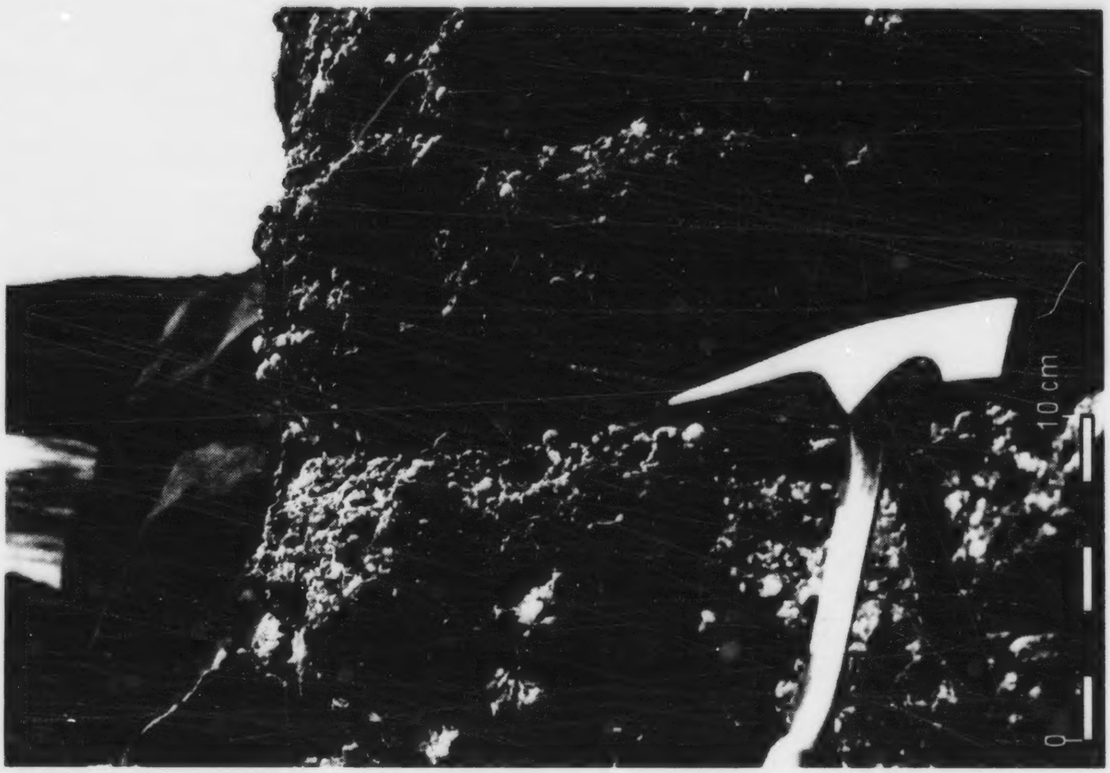


Figure 23b: Graded, pebbly gravel (transgressive lag) separating coarse grained, fluvial sediments of the Lower McMurray from fine grained, estuarine sediments of the Upper McMurray, Athabasca River, south of Tar Island (Suncor). Facies 2.

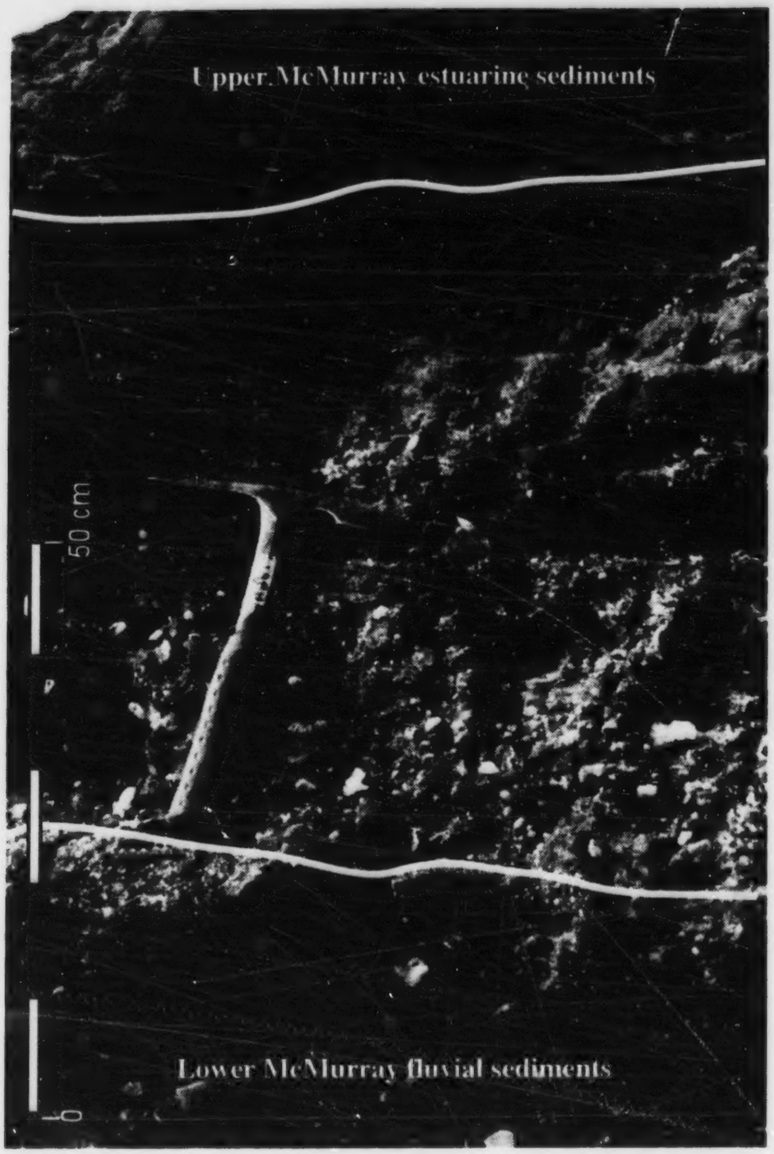

Upper McMurray estuarine sediments
50 cm
0
Lower McMurray fluvial sediments

Figure 23c: Fining upward pebbly gravel (transgressive lag) separating coarse grained, fluvial deposits of the Lower McMurray from fine grained, estuarine deposits of the Upper McMurray, Athabasca River, south of Tar Island (Suncor). Facies 2.

5.3 Facies 3: Carbonaceous to Coaly, Rooted Silty Mudstone

Facies 3 is a common facies, occurring within the Lower McMurray Formation, often associated with coarse-grained sediments and is rare in the Upper McMurray. Silty, light grey, carbonaceous, sometimes coaly mudstone with rare bioturbation (mainly horizontal *Planolites*) characterizes this facies (Figure 24a, 24b). Units of this facies average about 1.5 metres thick, ranging from 0.20 metres to amalgamated units exceeding 5 metres thick. Bedding within the silty mudstone facies is often contorted and slumped.

Carbonaceous mudstones of Facies 3 are most commonly found in the Lower McMurray associated with Facies 1, 2, 4, 17 and 18. Facies 3 has been observed in topographic lows on the pre-Cretaceous unconformity and encasing coarse-grained facies of the Lower McMurray (Facies 1 and 2). This facies can also be found, in rare cases, in the Upper McMurray succession associated with the muddier facies.

The carbonaceous mudstone has been observed in many cores from the McMurray Formation, but is poorly represented in outcrop. In core Facies 3 is recognized by the higher organic content of the mudstone, and the distinctive light to medium grey colouration (Figures 24a, 24b) that differs from the usual colour buff-tan grey colour of the more typical silty mudstone within the Upper McMurray succession. Carbonaceous mudstones of Facies 3 may grade both vertically and laterally into more organic coal-rich mudstones.

Interpretation: This facies is interpreted as being deposited from mainly suspension fallout and, less commonly, current washovers in vegetated overbank settings within the fluvially dominated environments of the Lower McMurray Formation. The environment where this facies is preserved has rare bioturbation features, which may be indicative of fresh water conditions in the fluvial realm. The facies is represented by overbank lakes, bogs and swamps associated with coarse-grained braided systems during Lower McMurray time. During Upper McMurray time, Facies 3 may have formed in similar environments such as fresh water lakes, swamps and vegetated muddy coastal plain deposits. Facies 3 is interpreted as one of the more common facies of the fluvial-dominated lowstand deposits and is a relatively rare facies within the overlying transgressive estuarine deposits.

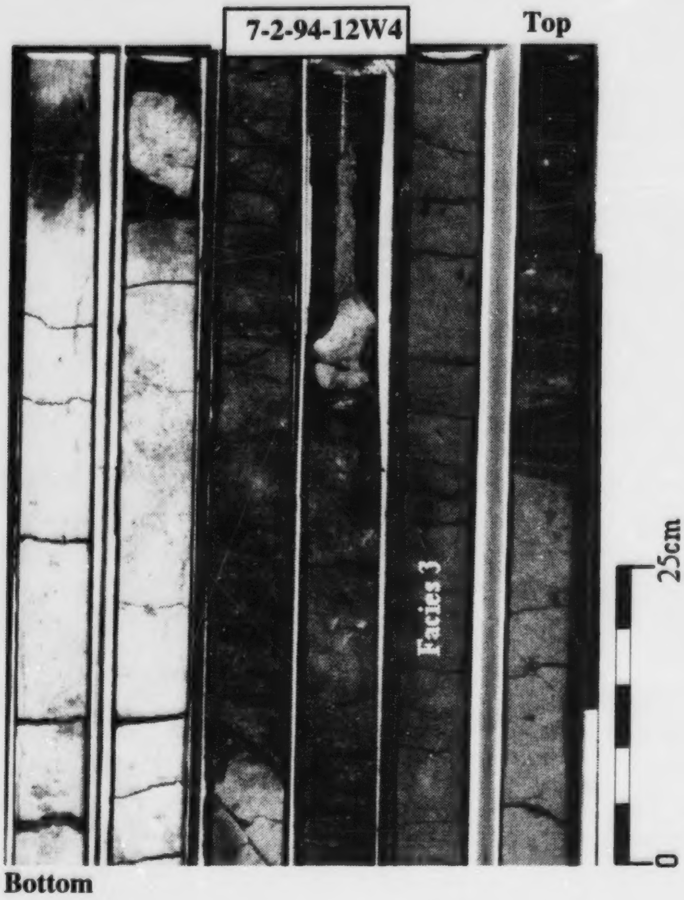
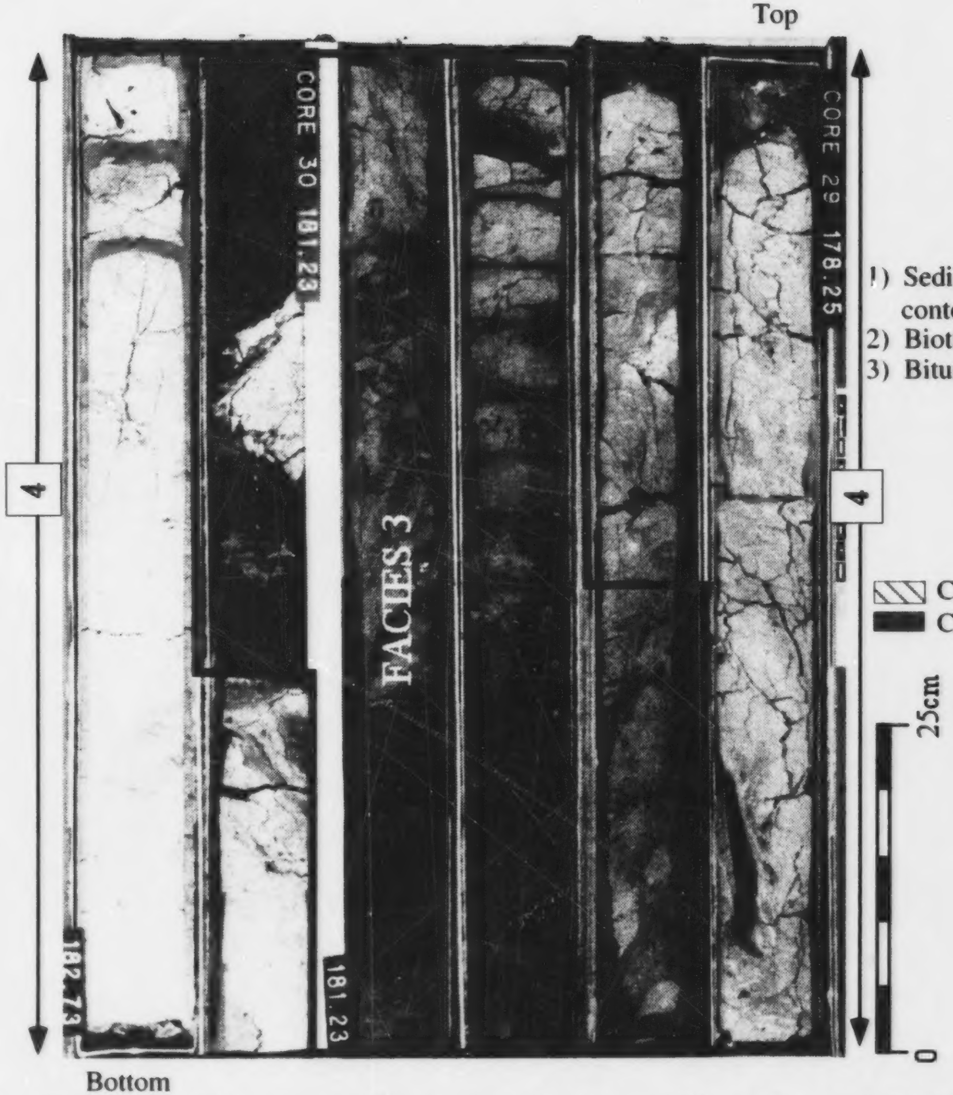

7-2-94-12W4
Top
Facies 3
25cm
0
Bottom

Figure 24a: Indurated, argillaceous sandy siltstone, siliceous and very slightly calcareous in cemented zones, overlain by light to medium grey, carbonaceous, organic rich, silty mudstone (right four core lengths). Facies 3, 4


Top
CORE 29 178.25
CORE 30 181.23
181.23
182.73
FACIES 3
4
4
25cm
0
Bottom

1) Sedimentary Features: coaly contorted bedding
2) Bioturbation Index: 1
3) Bitumen Saturation: nil

▨ Cored Interval
■ Core Interval Viewed

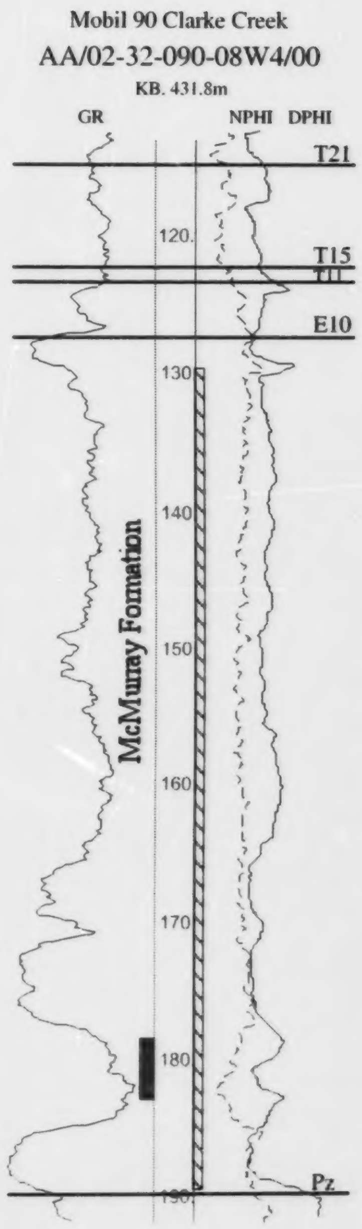


Figure 24b: Waxy, very carbonaceous sandy clay, possible marl, overlain by light gray to medium dark gray/brown, carbonaceous, organic rich, silty mudstone Facies 3, 4.
Geophysical log response shown to the right

5.4 Facies 4: Mottled Argillaceous Sandy Marl

Facies 4 is a rare unit generally confined to the basal part of Lower McMurray Formation. Locally, at outcrops of the McMurray Formation, along the Athabasca River near Daphne Island, this unit also occurs higher upsection where it is found at the base of a fluvial channel succession that overlies an estuarine complex (cf. Cotterill *et al.*, 2000). Sandy and silty mudstone, often calcareous, with a greenish-grey or white colouration characterizes this unit (Figures 24, 25a, 25b). Facies 4 is usually thin and laterally discontinuous, averaging 1.5 m thick (ranging in thickness from 0.2 to 4.0 m). Diffuse pedogenic mottling occurs. Thd facies is largely unindurated, and in outcrop mainly slumped. Carbonaceous material is sometimes preserved within the sediment as dispersed debris and coaly interbeds, or as local root casts.

The clay has an 'altered' appearance with an abundance of large-white micas that may be sericite. The altered appearance and high-clay content to the unit gives it a ' badlands type 'of weathering pattern. Scattered large rounded quartz pebbles occur in outcrop (Figure 25). Locally, where cemented, the cement is calcareous or sideritic. Rare organic mudstones and coaly interbeds are associated with this unit; and locally, there may be concentrations of ferrigunous nodules and/or sulphide mineralization near upper or lower contacts with more porous sandy units. Pyrite is common both as nodules and cement; siderite cement and replacement is also common. Rare chalcopyrite, sphalerite and manganese mineralization has been observed in core.

Locally, less-altered, calcareous marl is developed that shows well developed parallel stratification, rare ripples, and slump structures, including convolute lamination, disrupted bedding and syn-sedimentary folds. These features are generally better seen in core than in outcrop because of the intense weathering and slumped nature to the outcrops.

Facies 4 is confined to portions of the Lower McMurray succession and is usually directly overlying the pre-Cretaceous unconformity. The unit is associated with Facies 1, 2, 6, 15, 12A, 7A and 7B. Within certain regions of the Athabasca deposit Facies 4 is relatively common at the base of the Lower McMurray succession, particularly within the main valley trend. Surface exposures are found along the Athabasca River, north of Fort McMurray.

Interpretation: This facies is interpreted as being lacustrine marls that formed in flooded alluvial valleys developed along the pre-Cretaceous karstic landscape. This is indicative of low amounts of clastic input, perhaps within freshwater or palustrine (paludal) limestone environments that formed temporary ponds or lakes associated with karst solution and flooding of the karstic landscape. Where vegetated or rooted, the facies is interpreted as being paleosols that developed in vegetated areas of floodplains overlying carbonates at the pre-Cretaceous unconformity. Facies 4 is part of the fluvial-dominated package. Despite the rare occurrence of Facies 4, paleogeographically it is important because of the clear indication this facies gives of deposition under conditions of relatively lower clastic sedimentation rates, in subaerial and vegetated settings.

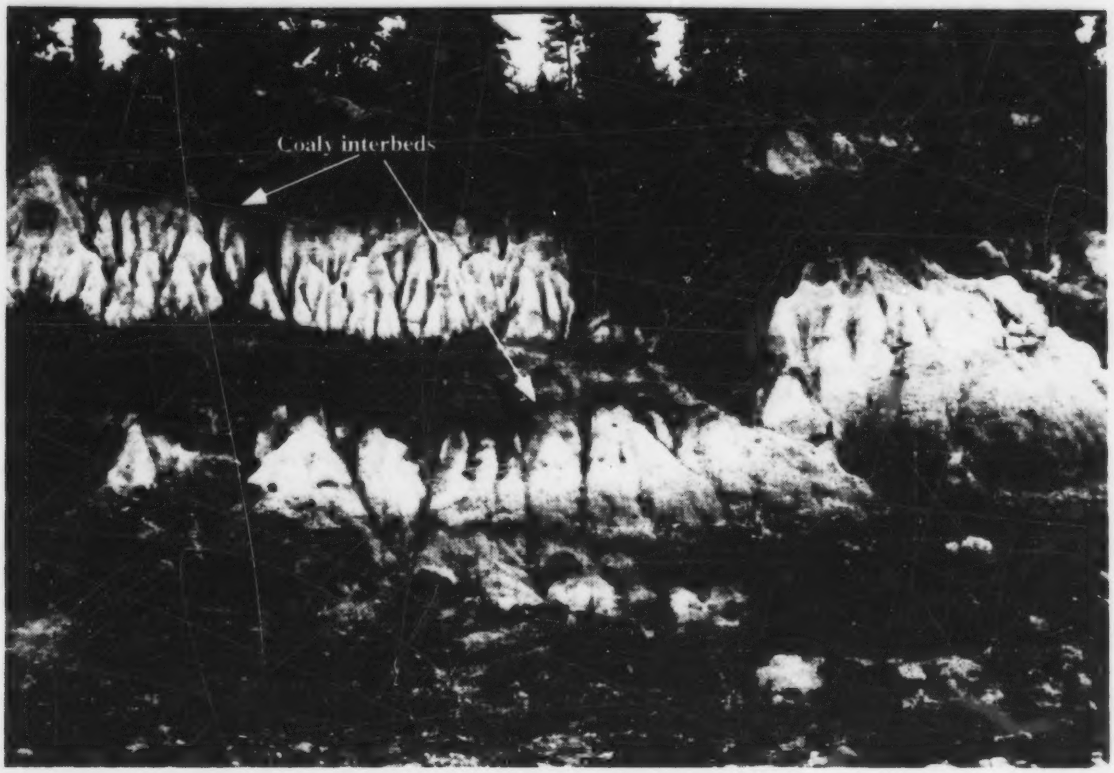


Figure 25: Mottled sandy marl with thin coaly beds occupying a paleotopographic low on the pre-Cretaceous unconformity, Lower McMurray Formation. East side of the Athabasca River, south of the confluence of the Steepbank and Athabasca rivers. Outcrop is about 5 metres high. Facies 4.

5.5 Facies 5: Fine to Medium Grained, Trough Cross Bedded Sand

Facies 5 can be found in both the Lower and Upper McMurray successions. Fine to medium grained, trough cross-bedded, quartz-dominated sand characterizes the unit (Figures 26 to 30). Beds average about 0.75 metres thick, ranging from 0.5 metres to greater than 1.0 metre. The sand is subangular to subrounded; most often moderately well sorted. Facies 5 is variably argillaceous ranging from very clean (no clay observed)(Figures 26, 27, 28, 30) to slightly argillaceous (Figure 29). Trough cross beds may extend 1 to 3 meters laterally along strike, and have an erosional top and base. Abundant mudstone clasts (5 to 15 cm in diameter) have been observed in core and outcrop. The unit sometimes contains rare, thin, discontinuous interbeds of light grey, silty mudstone. Facies 5 differs from Facies 1 in that is finer grained on average, and has much better sorting. Burrowing within Facies 5 is very rare with occasional in situ *Cylindrichnus* (Figure 29) and *Skolithos* burrows. However, it is common to find rip-up intraclasts comprised of mud-lined *Cylindrichnus* burrows caught up within the trough cross-bedded unit, particularly within later stage channeling events of the Upper McMurray Formation.

Facies 5 is most commonly found within the lower portions of the Upper McMurray succession often associated with Facies 6, 9A, 10A, 7A, 8A, 8B, 3, 10B, 15 and 16. Upward fining units of interbedded sand and mudstone commonly cap the facies. On the gamma ray log, amalgamated trough cross-bedded sands display a clean, blocky pattern often separated by thin mudstone breaks (Figure 30).

The fine to medium grained, trough cross-bedded sand facies has been observed on the Athabasca, Steepbank, Christina, Ells and MacKay rivers. The unit is usually limited in both vertical and lateral extent (vertical succession < 5 metres). In core, Facies 5 is recognized by prominent directional switching of paleoflows along apparent cross bedding trends (Figure 30).

Interpretation: This facies is interpreted as being deposited from three-dimensional sand dunes that migrated along the bottoms of river channels or formed the deeper and middle portions of sandy bars associated with fluvial and estuarine environments. In the Lower McMurray Formation these units are the dominant facies of the braided-fluvial complex. Within the Upper McMurray meandering estuarine channels, that flowed within confined valleys, resulted in complex facies associations, both vertically and laterally. Excessively thick intervals of amalgamated Facies 5 can often be attributed to stacked meandering channels in which successively younger channels erode the upper portions of pre-existing channels. In many cases the abandonment phase and point bar deposits have been removed leaving a succession of clean, blocky stacked units comprised of a series of channeling events through time as the estuary filled to base level. The somewhat common presence of out-of-place, reworked *Cylindrichnus* burrows within the trough cross beds provides good evidence for repeated erosional cut and fill events within the Upper McMurray. Facies 5 is interpreted as one of the common facies of the transgressive system during Upper McMurray time in the Athabasca region.

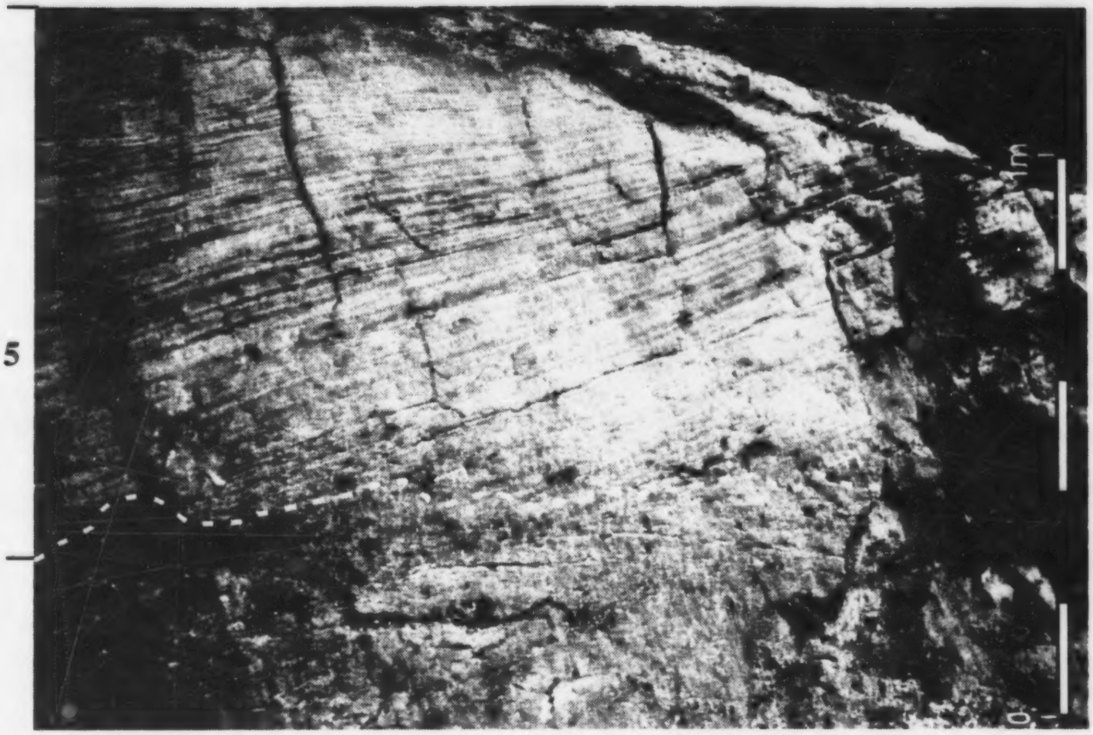


Figure 26: Bitumen stained, large scale trough cross-bedded sand (Facies 5), overlying mudstone clast breccia (Facies 7A), and capped by rippled sand (Facies 9A), Upper McMurray Formation, Saline Creek, Fort McMurray. Facies 5 (7A, 9A).

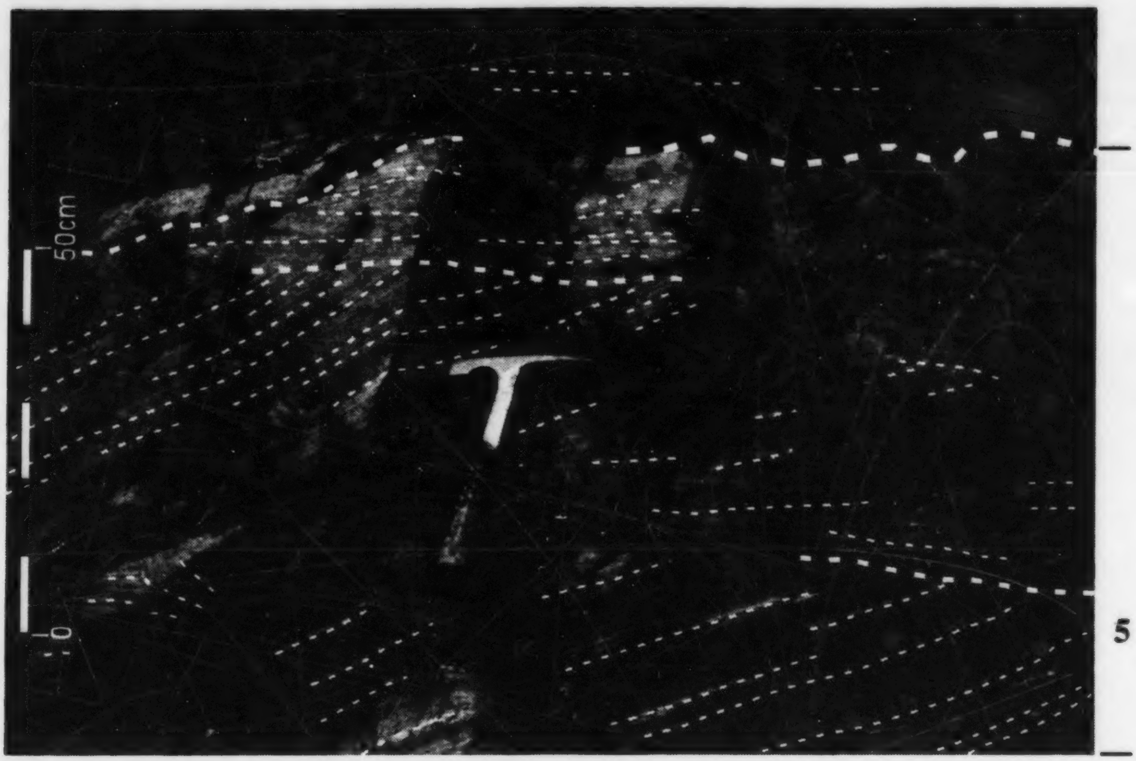


Figure 27: Large to medium scale, trough cross-bedded, sand, interbedded with rippled sand, Upper McMurray Formation. Dominant paleoflow direction to the north, from right to left. Twenty metres above the base of section #9-2, Steepbank River. Facies 5.

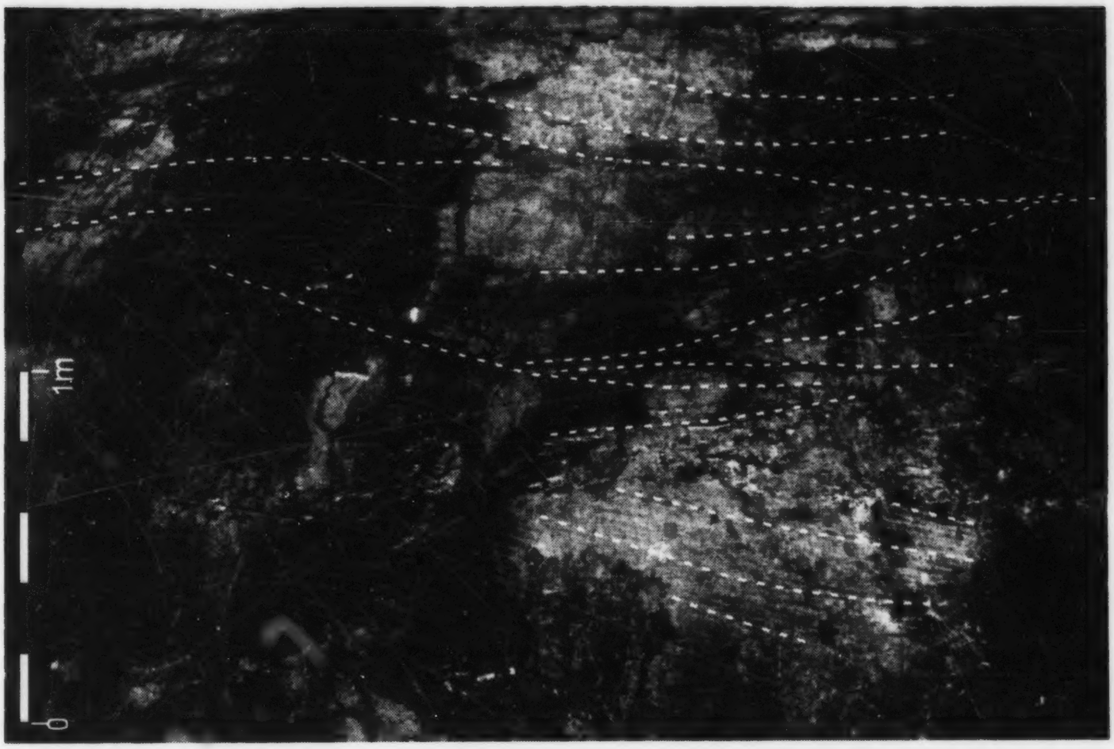


Figure 28: Medium to large scale, trough cross-bedded, medium grained sand, Upper McMurray Formation. Fourteen metres above the base of section #4-1, Steepbank River. Dominant paleoflow direction to the north, out of the page. Facies 5.

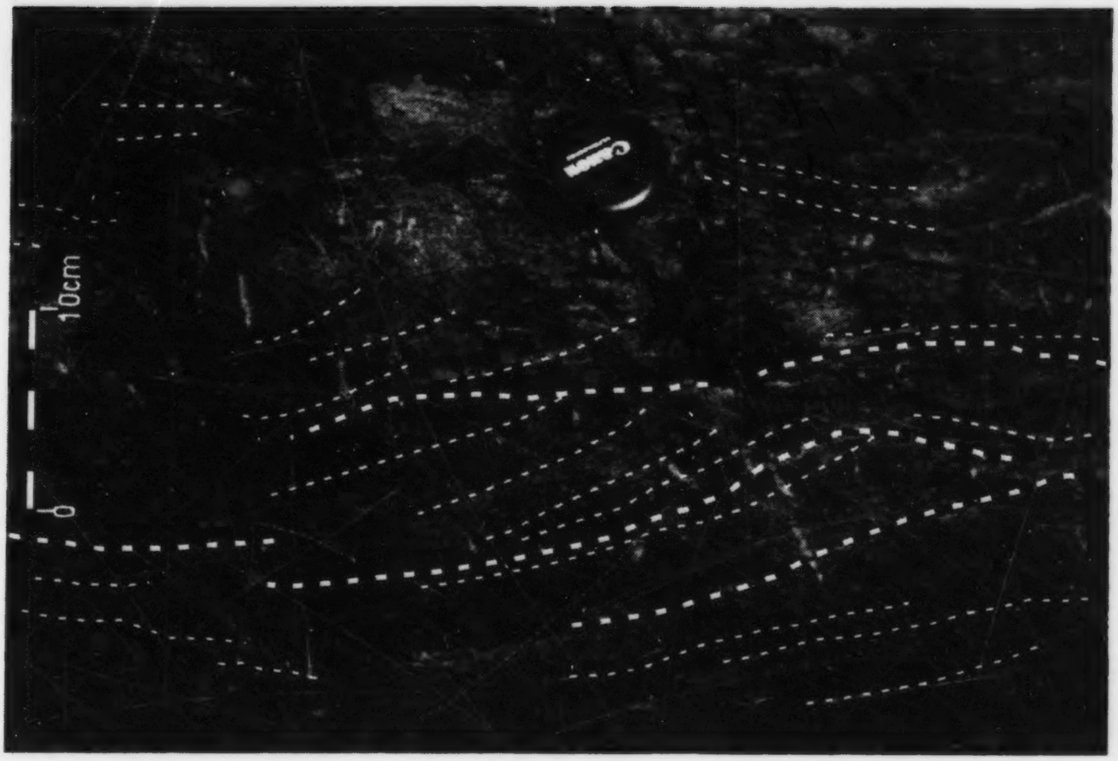
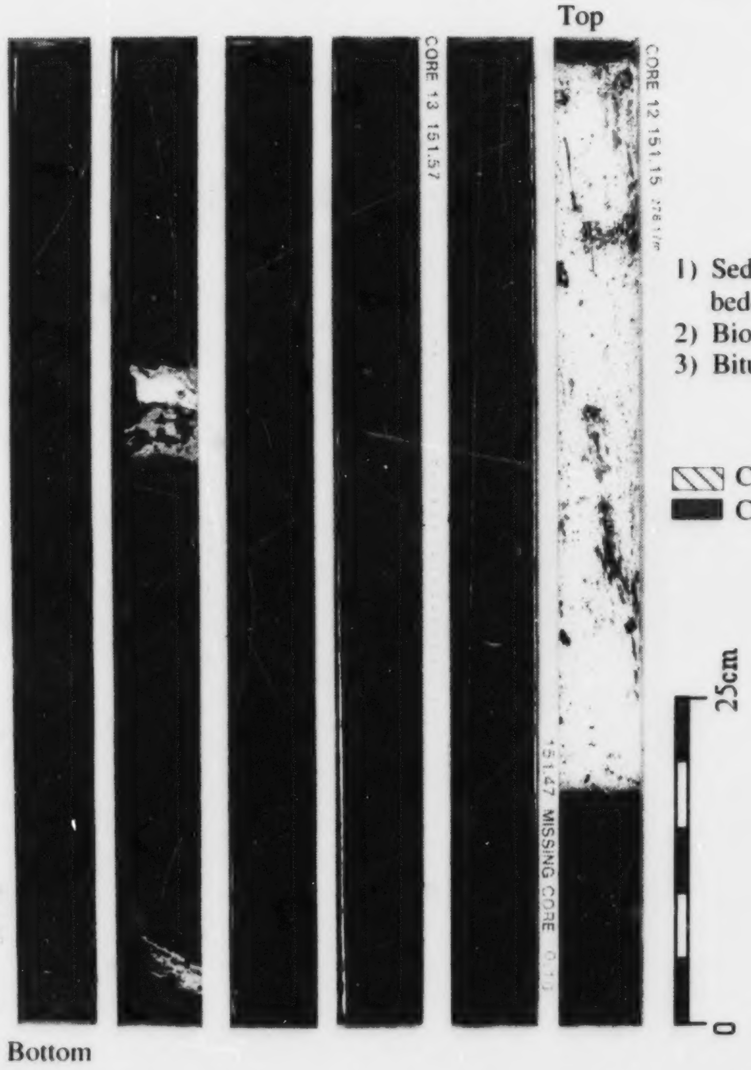


Figure 29: Small scale, trough cross-bedded sand, with in situ *Cylindrichnus* burrows. Upper McMurray Formation, Outcrop #3, Steepbank River. Dominant paleoflow direction to the north, from right to left. Facies 5.


Top
CORE 12 151.15
151.47 MISSING CORE
CORE 13 151.57
Bottom
25cm
0

1) Sedimentary Features: trough-cross bedding
2) Bioturbation Index: 0
3) Bitumen Saturation: excellent

▨ Cored Interval
■ Core Interval Viewed

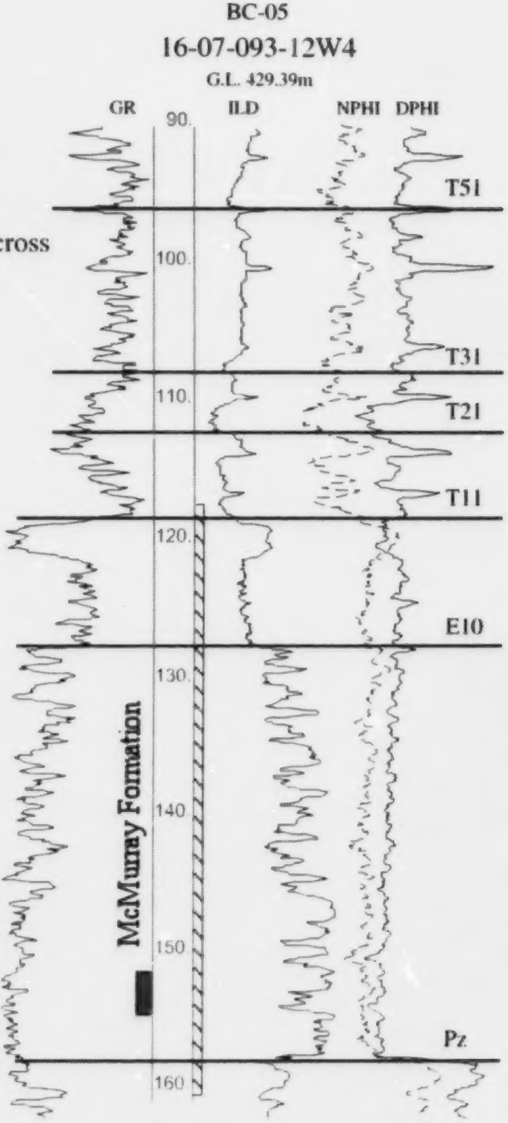


Figure 30: Heavily bitumen-stained, trough cross-bedded, fine grained sand, with scattered burrowed mudstone clasts, Upper McMurray Formation. Facies 5.
Geophysical log response shown to the right.

5.6 Facies 6: Fine Grained to Pebbly, Planar-Tabular Cross Bedded Sand

Facies 6 is relatively common in both the Lower and Upper McMurray Formation. Fine to coarse grained, sometimes granular to pebbly, planar-tabular cross bedded, quartz-dominated sand characterizes the unit (Figures 31 - 35). Individual beds average about 0.5 metres thick, ranging from 0.2 to 2 metres thick. Amalgamated beds greater than 10 metres thick have been observed in both core and outcrop (Figure 31). The sand is fine grained to pebbly, subangular to subrounded and is most often moderately well sorted. Planar-tabular cross bed sets may extend for tens of metres laterally (observed in outcrop, Figure 31). Beds have sharp erosional bases. Bed toeset terminations are either angular or tangential (Figure 32, 33). Within the Upper McMurray the larger scale bedforms are usually found within the lower portions of the succession, with bedform size generally decreasing in size upsection. Facies 6 is most often associated with trough cross-bedded (Facies 5, Figure 31), rippled (Facies 9A, Figure 32, 33) and massive (Facies 8A) sands. In some instances, a subtle variation in sorting of the sands along cross beds has resulted in a prominent variation in bitumen staining (Figure 34).

The coarse to pebbly sand component of Facies 6 is most common in the Lower McMurray and is often associated with Facies 1. The fine to medium-grained, planar-tabular cross-bedded sand is very common within the Upper McMurray Formation, where Facies 6 is commonly associated with Facies 5, 9A, 10A, 10B and 11. On the gamma ray log the facies usually displays a thick, clean, blocky profile with minor muddy interbeds (Figure 35). In core, Facies 6 is recognized by prominent and well-defined high angle, planar tabular cross bedding and apparent unidirectional foreset dip directions (Figure 35).

The fine grained to pebbly, planar tabular cross bedded sand facies has been observed on the Athabasca, Steepbank, Christina, Ells and MacKay rivers, and is excellently exposed along Saline Creek. Within the Upper McMurray the vertical bed height tends to be larger near the base, decreasing in size up section (eg: Steepbank Outcrop #9). Lateral continuity ranges from just a few metres to the entire length of some exposed sections.

Interpretation: This facies is interpreted as being deposited from two-dimensional coarse grained sand dunes that migrated along the bottoms of river channels or formed the slipfaces of sandy braid bars or sand-flat complexes now preserved as fluvial deposits of the Lower McMurray Formation. In the Upper McMurray Formation, Facies 6 is similarly interpreted as being deposited from finer grained sand waves that migrated along the bottoms of meandering estuarine channels or formed the slipfaces of sandy bars or sand- flat complexes within the fluvial-estuarine valley complex. Very thick, amalgamated packages of Facies 6 are likely part of a less confined, high-energy open estuarine system. Facies 6 is interpreted as one of the subordinate facies of the fluvial lowstand systems and a common facies within the overlying transgressive system.

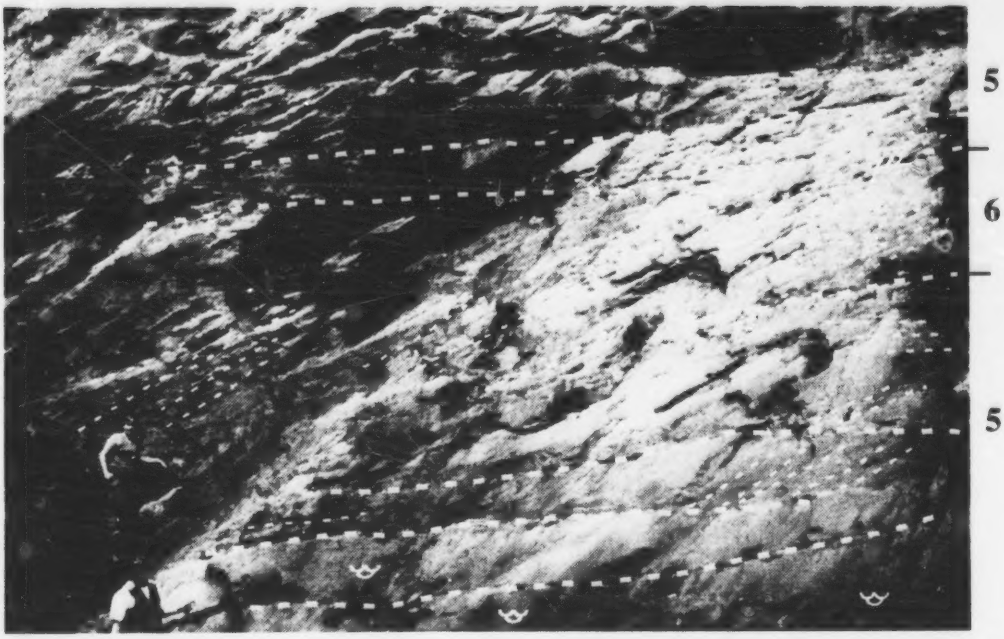


Figure 31: Stacked, large-scale planar tabular cross-bedded sand (Facies 6) underlain by trough cross-bedded sand (Facies 5), Upper McMurray Formation, Saline Creek, Fort McMurray. Approximately 10 metres of section shown.

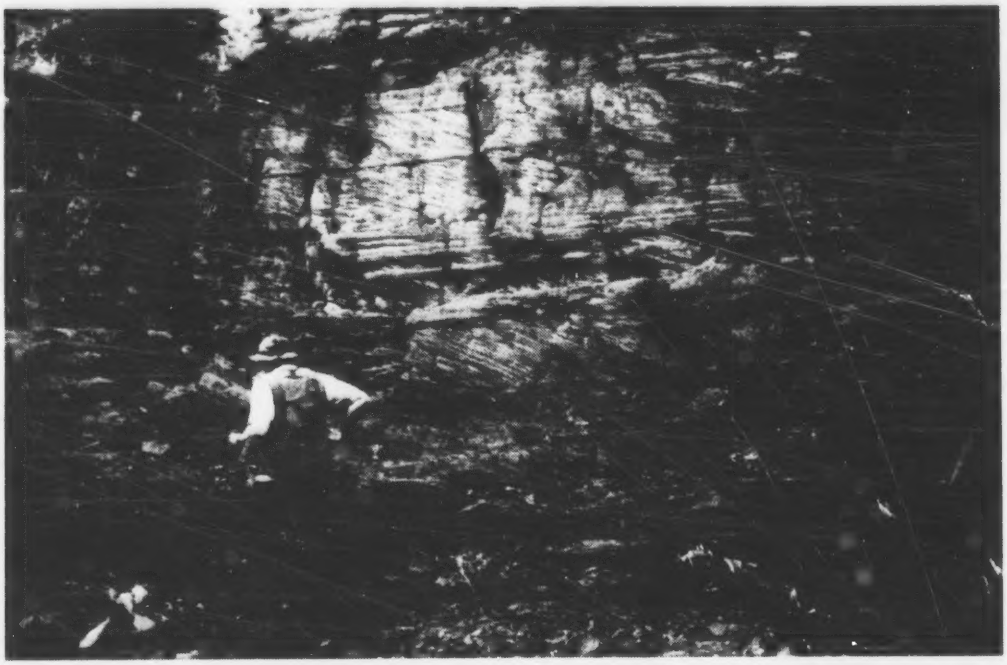


Figure 32: Stacked, high angle, planar tabular cross-bedded sand (Facies 6) interbedded with thin (>10 cm) rippled sand (Facies 9A), Lower McMurray, Ells River.

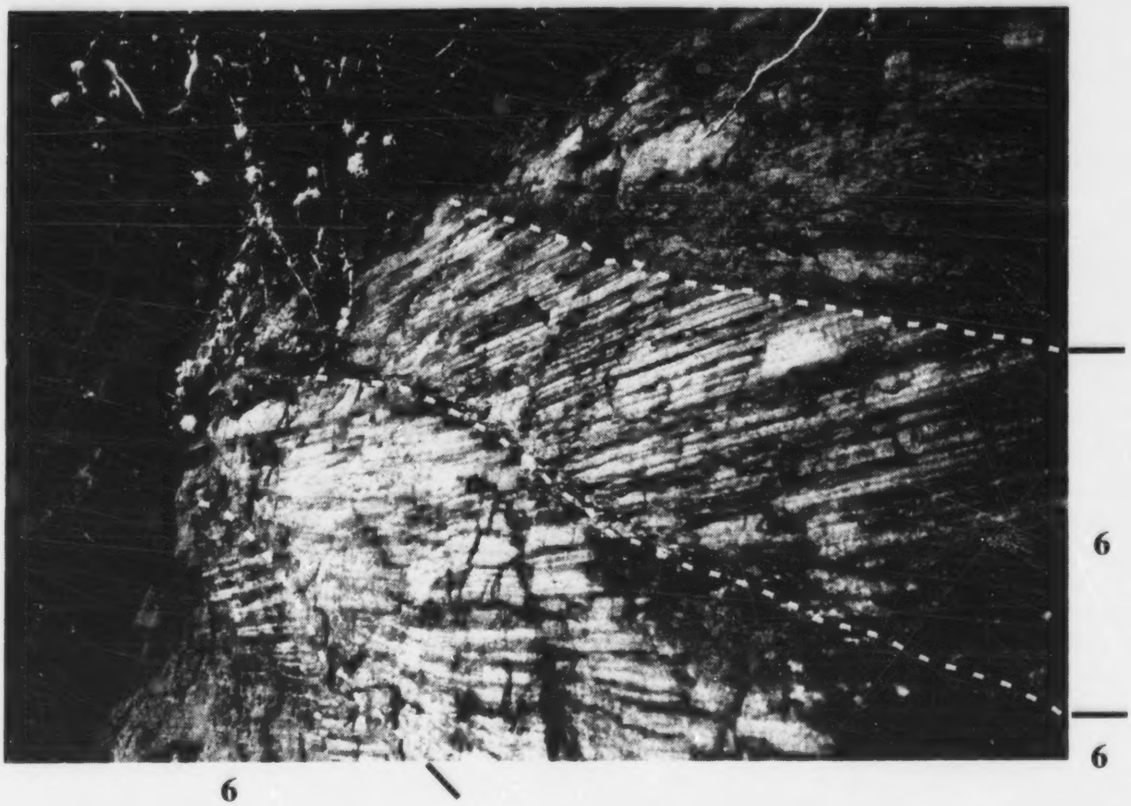


Figure 33: Stacked, medium-scale, planar tabular cross-bedded sand (Facies 6) capped by rippled sand (Facies 9A), Upper McMurray Formation, Saline Creek, Fort McMurray. Dominant paleoflow direction to the north, from right to left. About 2 metres of vertical section is shown in the photograph. Facies 6, 9A.

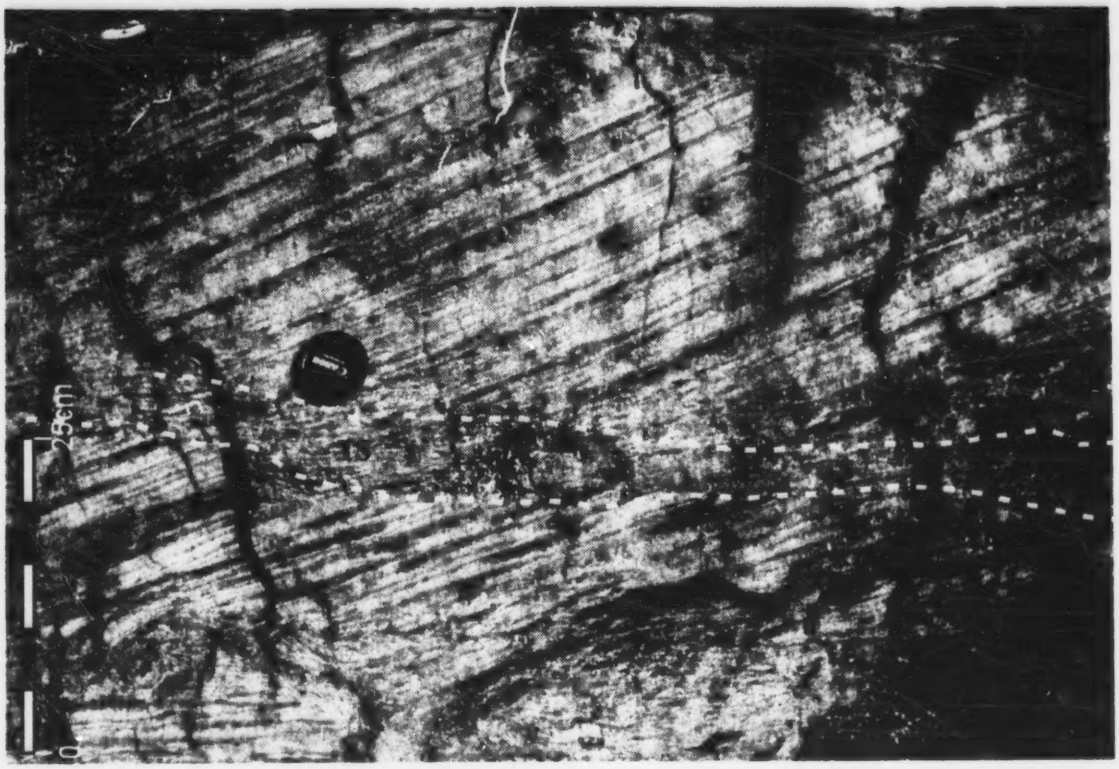


Figure 34: Stacked, medium scale, planar tabular cross-bedded sand (Facies 6) with toeset (TS) rippled sand, showing minor convolute bedding at the base (dashed lines, Facies 9A), Upper McMurray Formation, Saline Creek, Fort McMurray. Dominant paleoflow direction to the north, from right to left. Facies 6, 9A.

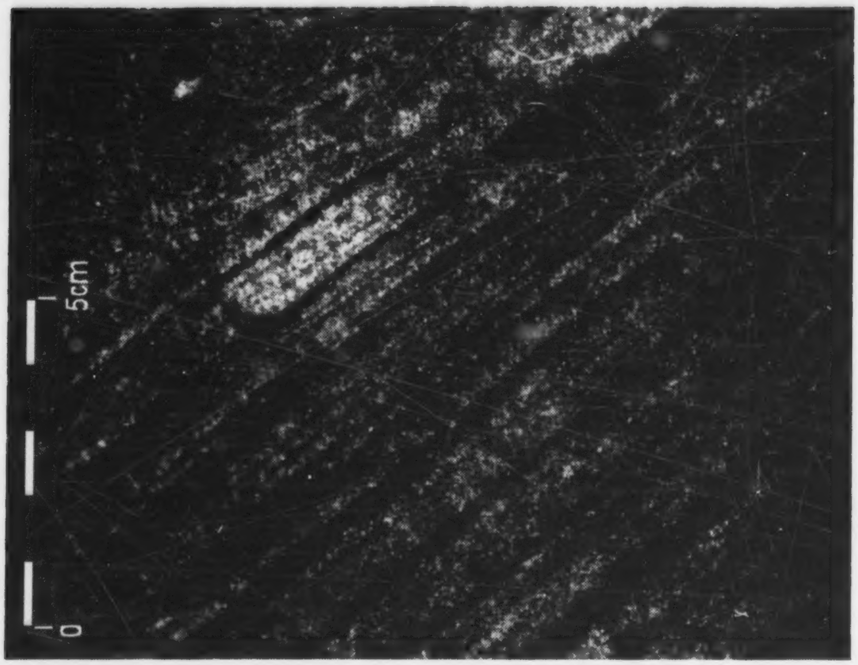


Figure 35: Detail of planar tabular cross-lamination in sand showing subtle variations in bitumen saturation, with heavy saturation in better sorted sand, and poor saturation in more poorly sorted fine sand and silt, Upper McMurray Formation. Amphitheatre outcrop, MacKay River. Facies 6.

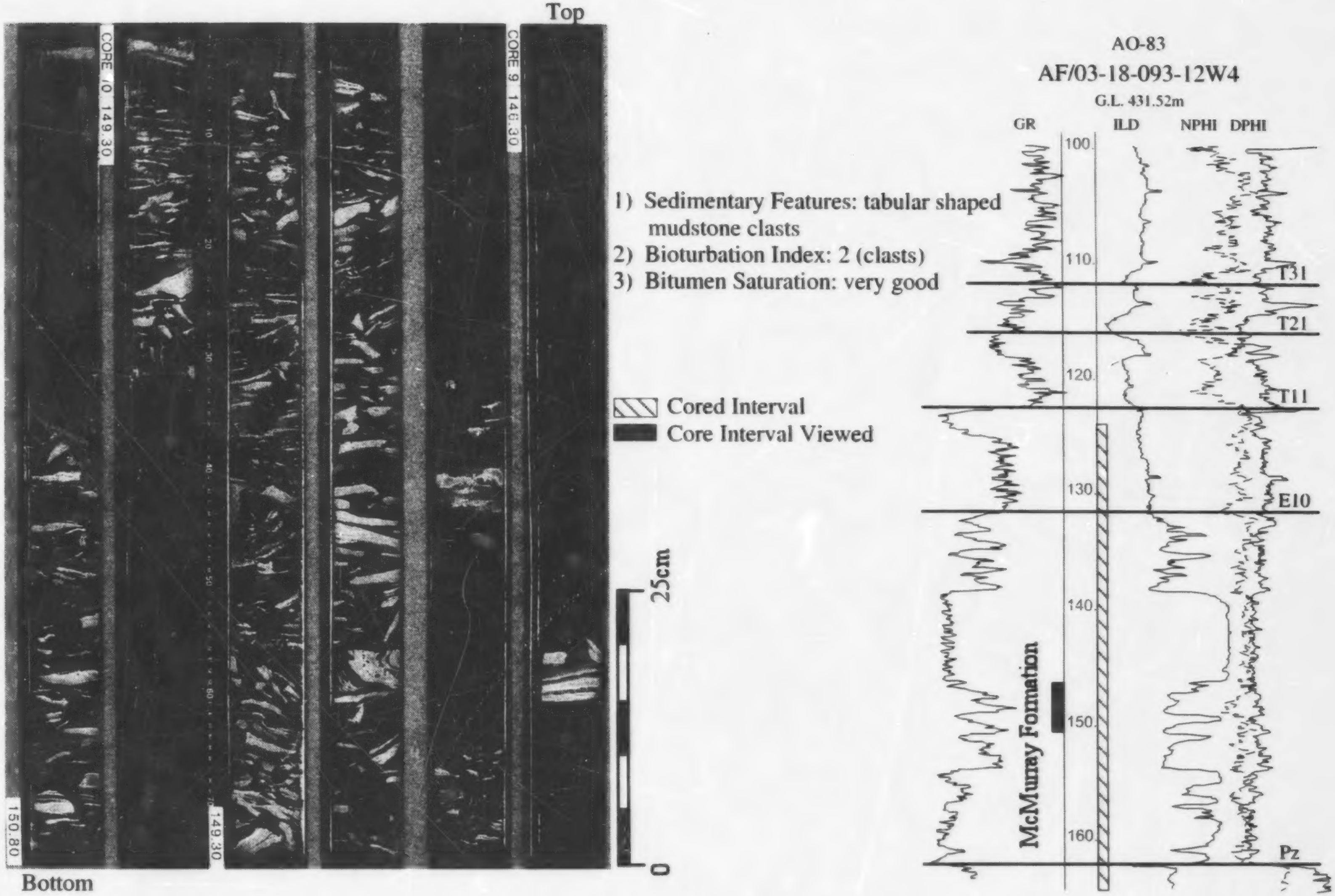
5.7A Facies 7A: Fine to Medium Grained, Poorly Sorted, Mudstone-Clast Breccia

Facies 7A is dominated by syndepositional mudstone clast breccia (i.e. intraclasts) that generally has an unburrowed sandy matrix. Internally mudstone clasts are not bioturbated (or rarely) in the Lower McMurray and are commonly bioturbated (prior to redeposition as clasts) in the Upper McMurray. Facies 7A is common in both the Lower and the Upper McMurray. Fine to medium grained sandy, poorly sorted, mudstone clast breccia characterizes the unit (Figures 36, 37). Mudstone clast breccia units are variably thick, ranging from single mudstone clast lags (< 0.1 m thick) to amalgamated units exceeding 5 metres thick. Breccia beds are mainly matrix-supported, less commonly clast-supported (Figures 36, 37). The sand matrix is well sorted and subangular (Lower McMurray) to well rounded (Upper McMurray). Breccia units generally have limited lateral extent; have an erosional base; and, generally a transitional top. Coal detritus and mummified logs may occur within the breccias, or communited organics may be disseminated throughout the sandy matrix. Porosity and permeability values are quite variable within this facies and, in core and outcrop, 'water shadows' within otherwise bitumen saturated zones may occur in the lee of the mudstone clasts. Mudstone clast fabrics are variable, from random to shingled (a-axis imbrication).

This facies is much more common in the Upper McMurray succession, and in cases where mudstone clast breccias overlie and/or rework mudstone clast breccias of the Lower McMurray Formation, distinction of the two units is very difficult. Within the Lower McMurray Formation mudstone breccias are also occassionally composed of reworked marl deposits that are not found in the Upper McMurray. Facies 7A units often underlay or interfinger laterally with the inclined heterolithic sands of Facies 10A and is commonly interbedded with Facies 1 and 2.

The mudstone clast breccias have been observed in many outcrops on the Athabasca, Steepbank, Ells, Hangingstone, Christina and MacKay rivers. In outcrop Facies 7A is most often laterally discontinuous (over a few metres) present as thin lenses or less commonly found in small cut and fill features. In core Facies 7A is recognized by the prominent and well-defined mudstone clasts dispersed or concentrated in beds with a sandy matrix. On the gamma ray log Facies 7A is difficult to distinguish from interbedded silty or sandy mudstones (Figures 36, 37). In this instance the dipmeter log, if available, may aid in identifying the breccia facies. The dipmeter will likely show random dip and dip directions over short intervals (provided the dipmeter interval resolution is satisfactory) within the brecciated zone as opposed to more uniform, continuous readings within the interbedded sandy/silty mudstone units.

Interpretation: This facies is interpreted as being deposited from unidirectional flow currents that occurred along the cut-bank margins of meandering fluvial or estuarine channels, or as part of the lower parts of muddy point-bar lateral accretion deposits that slumped and were redeposited within the adjacent cut-bank channel. These breccias form part of the normal processes of cutbank–point bar erosion-and-migration associated with meandering fluvial-channel flows in Lower McMurray time, and as part of the normal meandering tidal-estuarine channel flows in Upper McMurray time. Facies 7A is interpreted as one of the common facies of both the fluvial lowstand and the estuarine transgressive deposits.


Top
CORE 9 146.30
CORE 10 149.30
149.30
150.80
Bottom
25cm
0
GR
ILD
NPHI
DPHI
100
110
120
130
140
150
160
T31
T21
T11
E10
Pz
McMurray Formation

AO-83

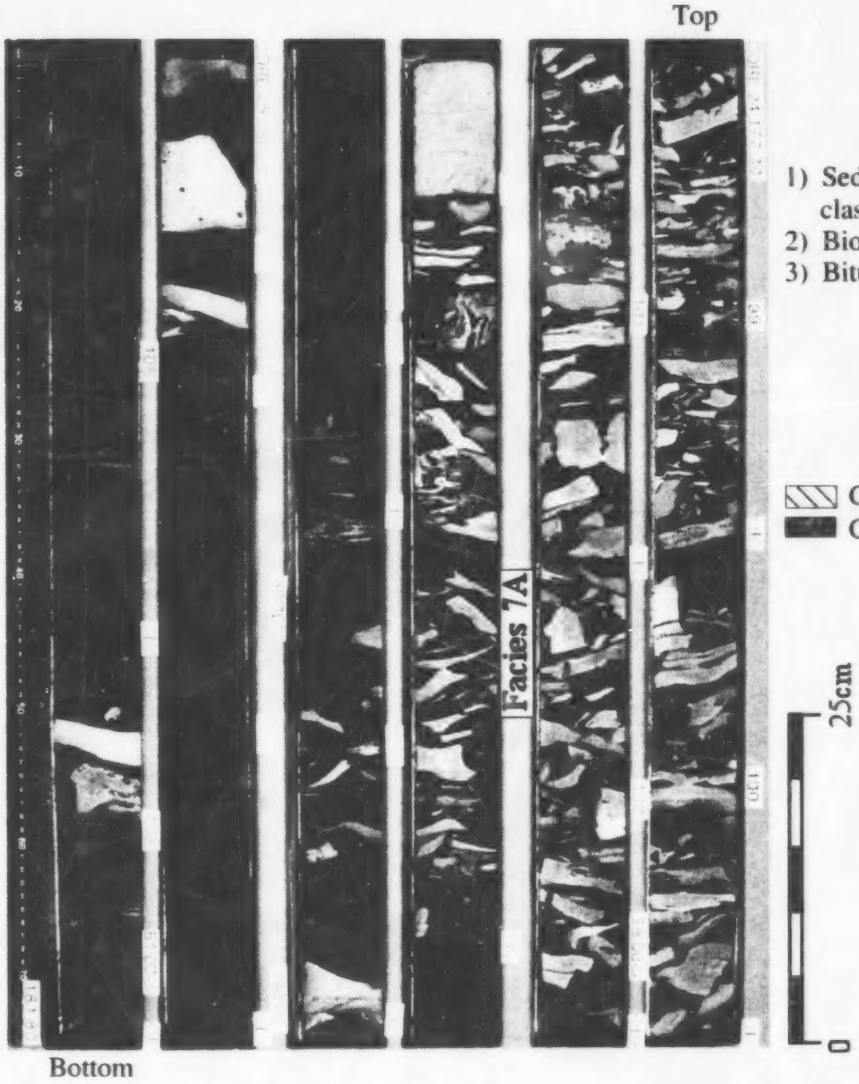
AF/03-18-093-12W4

G.L. 431.52m

1) Sedimentary Features: tabular shaped mudstone clasts
2) Bioturbation Index: 2 (clasts)
3) Bitumen Saturation: very good

▨ Cored Interval
■ Core Interval Viewed

Figure 36: Bitumen saturated, matrix supported mudstone-clast breccia, interbedded with thin massive sand, Upper McMurray Formation. Facies 7A (8A).
Geophysical log response shown to the right.



1) Sedimentary Features: mudstone clast breccia
2) Bioturbation Index: 1-2 (clay clasts)
3) Bitumen Saturation: very good

▨ Cored Interval
■ Core Interval Viewed

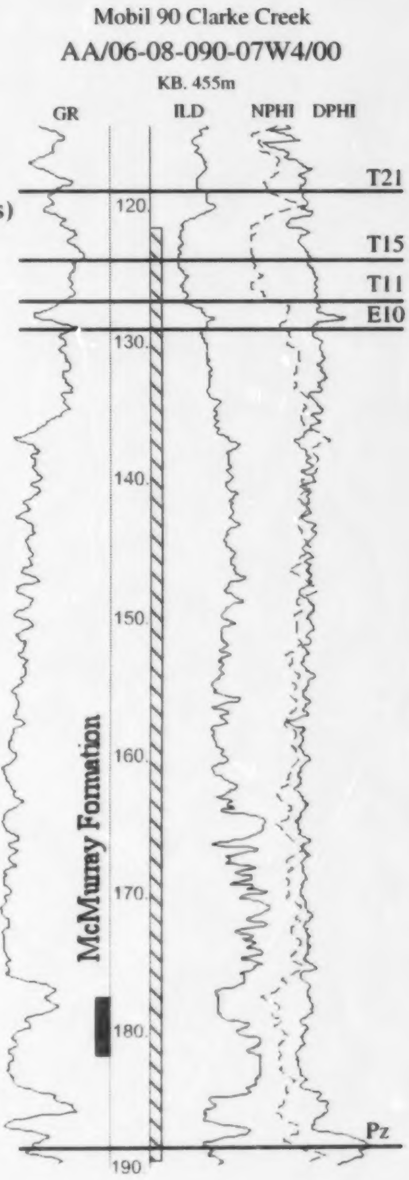


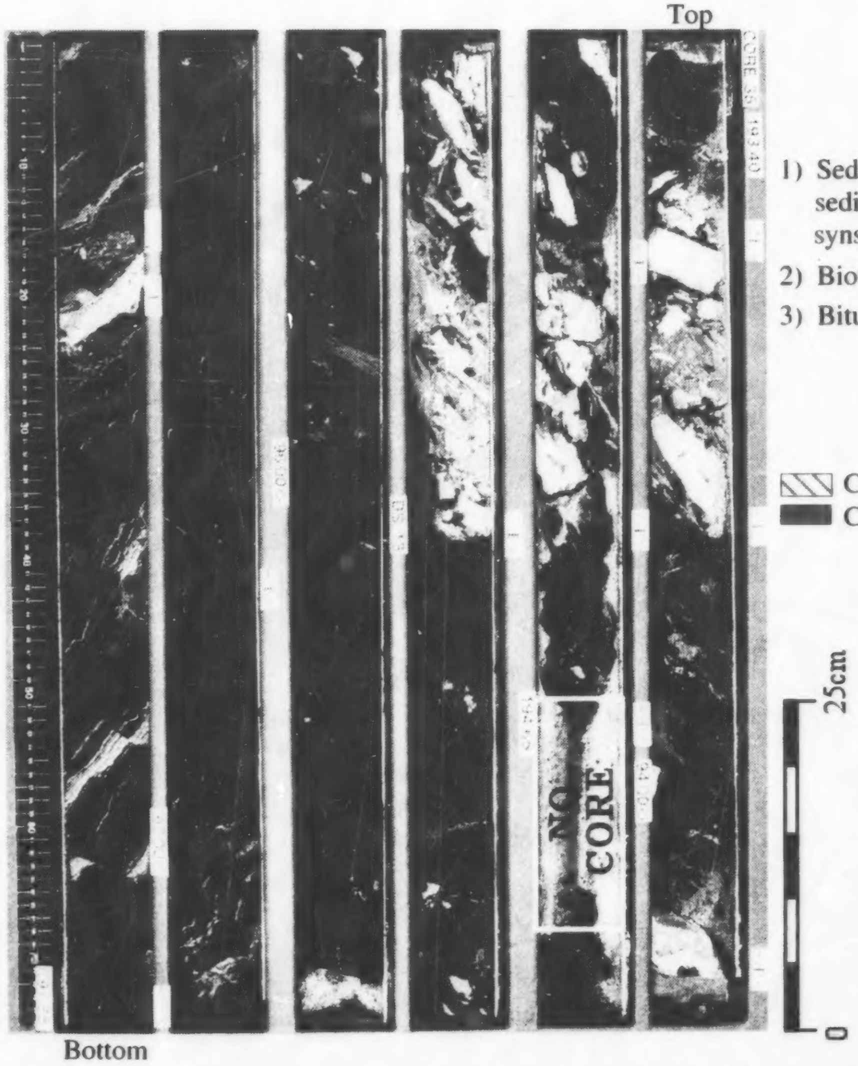
Figure 37: Heavily bitumen-stained, matrix-supported mudstone-clast breccia, interbedded with massive sand at the base, Upper McMurray Formation. Facies 7A (8A). Geophysical log response shown to the right.

5.7B Facies 7B: Slumped Sand and Mudstone

Facies 7B is an uncommon to rare facies, found in both the Lower and Upper McMurray successions. The characteristic feature of the facies is the occurrence of synsedimentary folds or brecciation (or slump structures) that have affected sediment of any lithology, from mud and silt, to coarse sand and gravel material (Figures 38 to 41). Slumped units average 1.5 metres thick, ranging from about 0.5 metres to 3.5 metres thick. Less commonly carbonaceous material, coalified or mummified logs are caught up in the slumped material.

Rarely slump deposits are interbedded with the organic, carbonaceous and coaly mudstone and rooted paleosols (Figure 40). In core Facies 7B is recognized by prominent and well defined folds, many of which are recumbent or overturned (Figure 39); oversteepened cross bedding, rotated and folded cross bedding (Figure 41) or rotated burrow structures; and brecciated/boudinaged and faulted sediment packages (Figures 38, 40, 41). Locally, at the base of the McMurray Formation, coarse clastic sand material has slumped into underlying sinkholes and other karst depressions within the underlying Devonian carbonates. Other occurrences of slumping are associated with mudstone-clast breccias (Facies 7A) as part of cut-bank/point bar erosion-and-migration.

Interpretation: This facies is interpreted as being deposited from sediment gravity flows that mobilized existing sedimentary packages and resedimented them locally within the depositional setting. Such remobilization was common along areas of paleotopographic relief, such as karst depressions along the unconformity, along steep channel margins that were incising into underlying sediment, on the edges of point-bars that were slumping into cut-bank channels, or as local material resedimented from bedrock highs into the surrounding fluvial and estuarine channel systems. Locally some of the remobilization may relate to later post-depositional slumping associated with dissolution of the Prairie Evaporite beneath the McMurray clastic succession.



1) Sedimentary Features: slumped sediment with small scale synsedimentary faulting
2) Bioturbation Index: 1
3) Bitumen Saturation: good

▨ Cored Interval
■ Core Interval Viewed

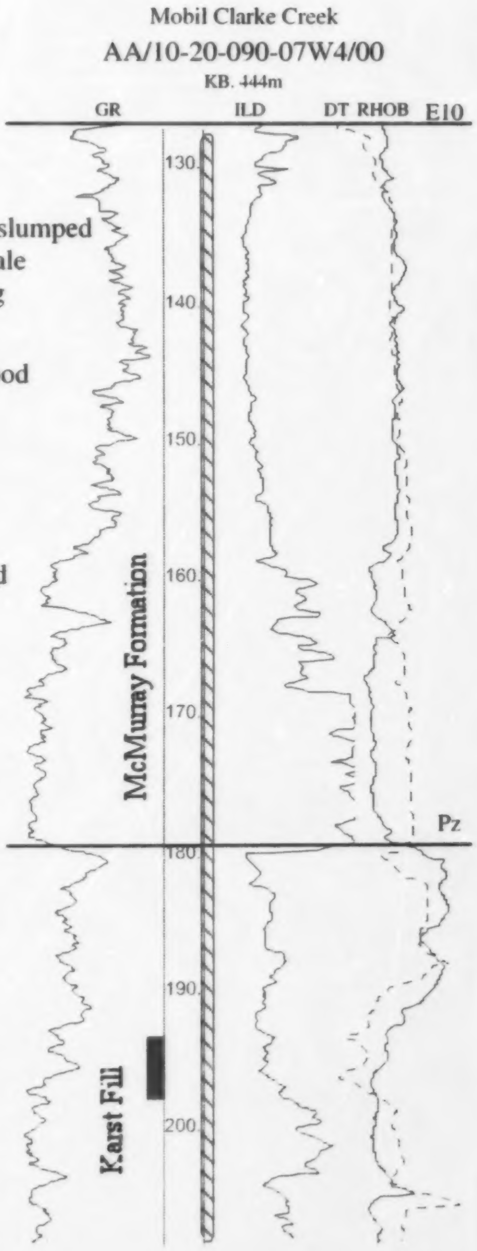
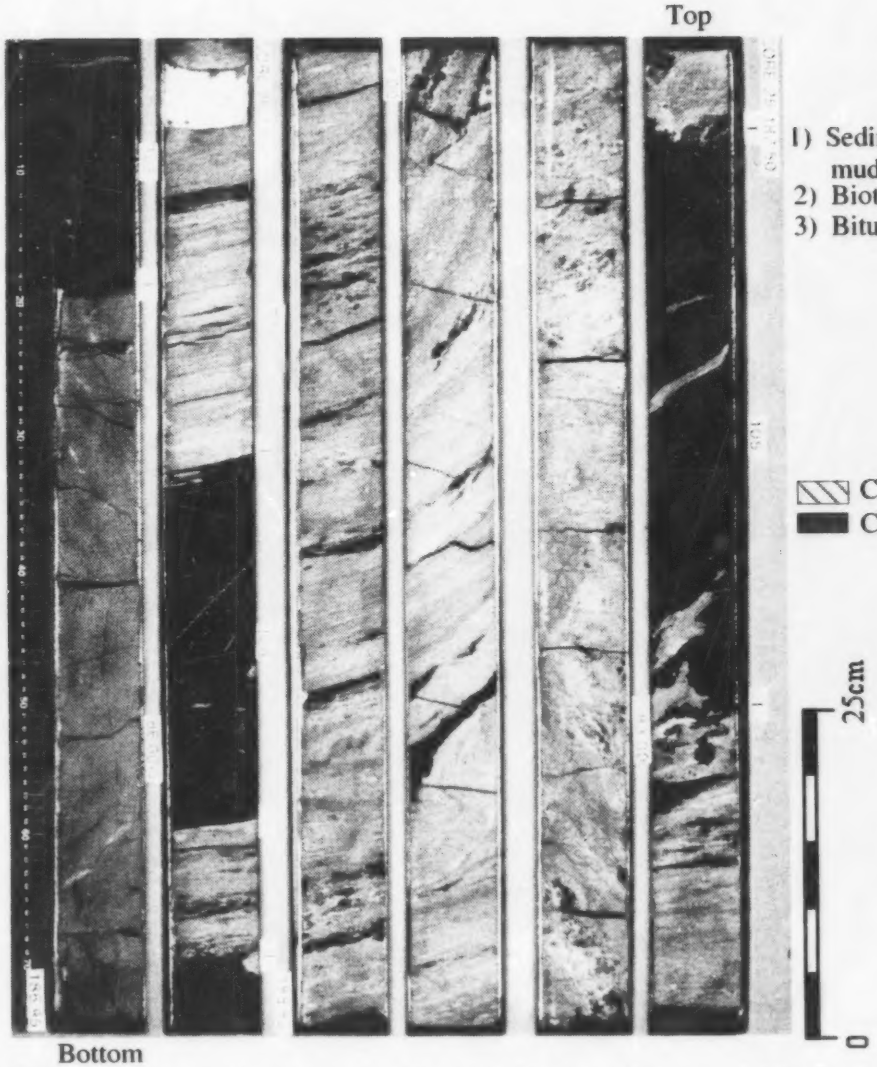


Figure 38: Heavily bitumen-stained, slumped, interbedded mudstone, sand and mudstone clasts, with synsedimentary faults in the lower 1/3 of the core shown, Upper McMurray Formation. Facies 7B. Geophysical log response shown to the right.



1) Sedimentary Features: slumped mudstone and mud clasts
2) Bioturbation Index: 2
3) Bitumen Saturation: poor to good

▨ Cored Interval
■ Core Interval Viewed

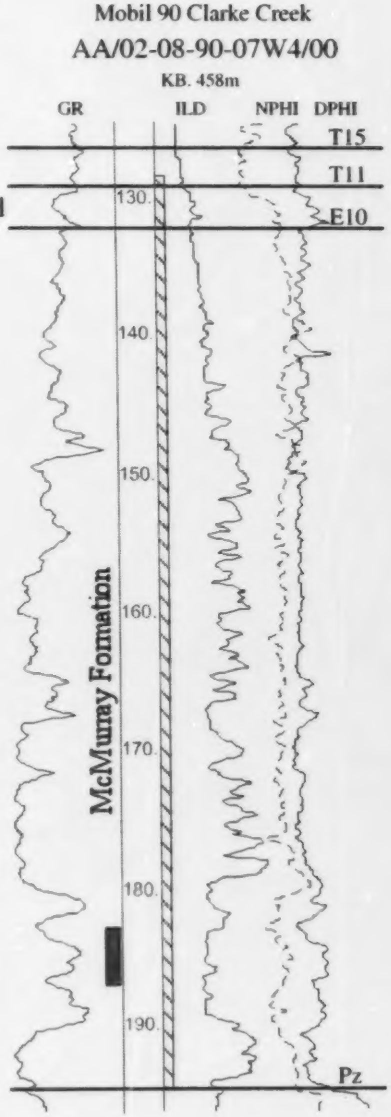
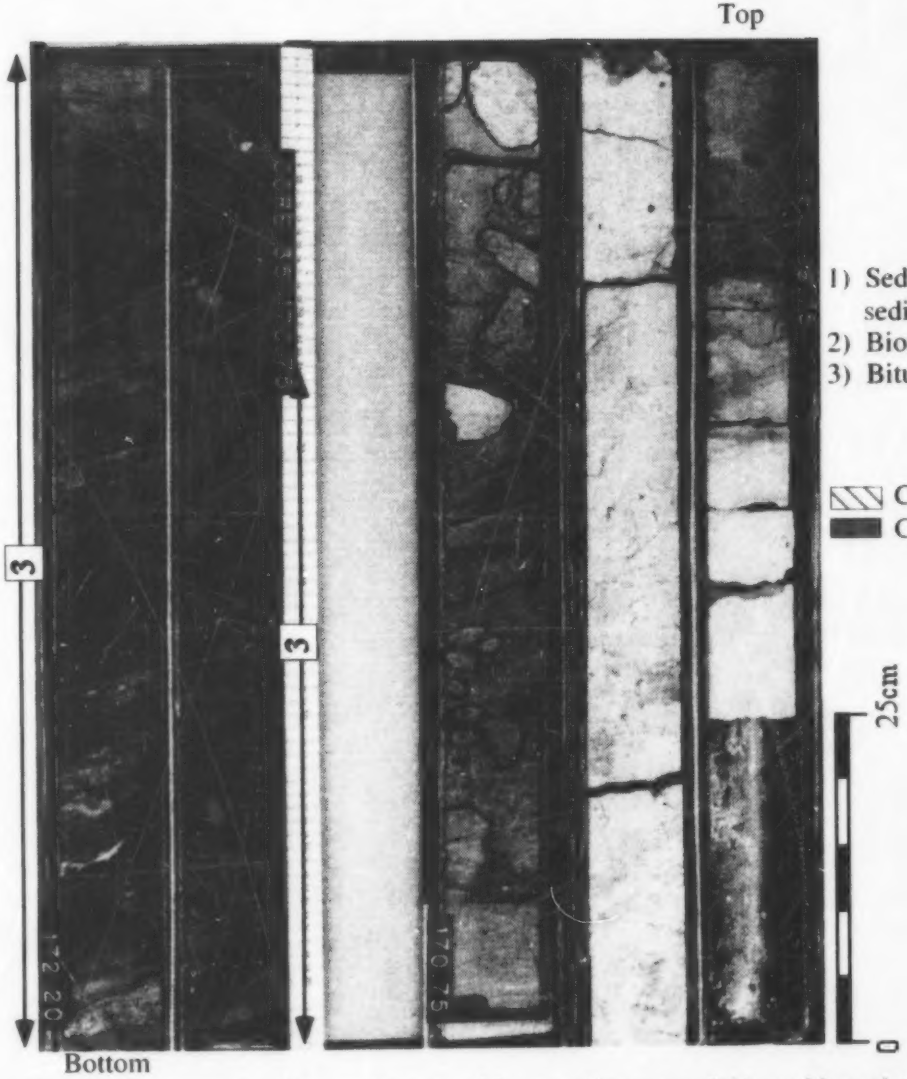


Figure 39: Slumped, sand and mudstone, with synsedimentary folding and oversteepened bedding, Upper McMurray Formation. Facies 7B. Geophysical log response shown to the right.


Top
Bottom
3
3
CORE 35 170.75
170.75
172.20
25cm
0

1) Sedimentary Features: slumped sediments
2) Bioturbation Index: 2
3) Bitumen Saturation: nil

▨ Cored Interval
■ Core Interval Viewed

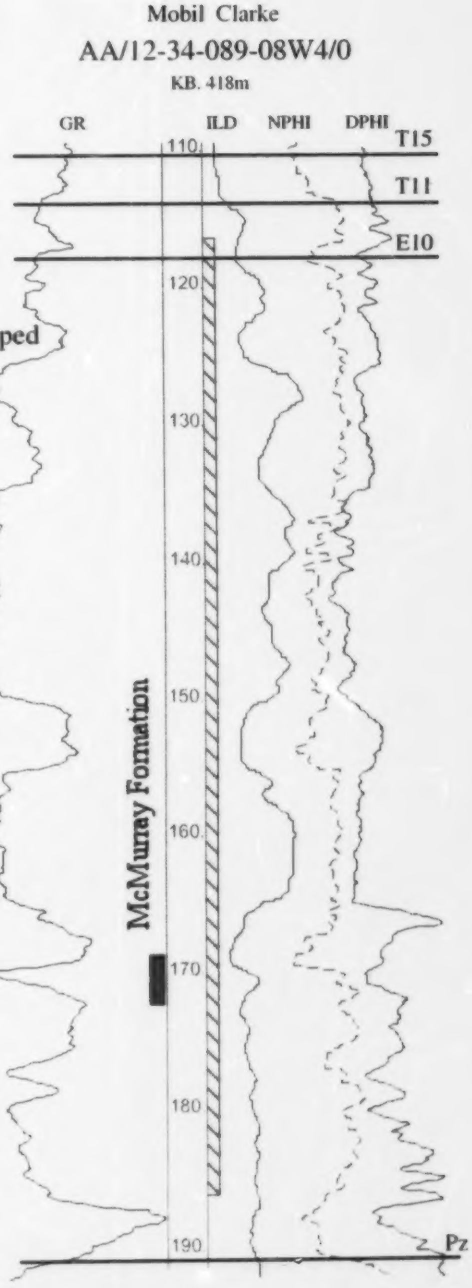


Figure 40: Slumped silty mudstone, with synsedimentary folds and brecciation, carbonaceous to coaly silty mudstone (Facies 3), and overlain by rooted, very fine silty mudstone (Facies 4), Lower McMurray Formation. Facies 7B (3, 4). Geophysical log response shown to the right.

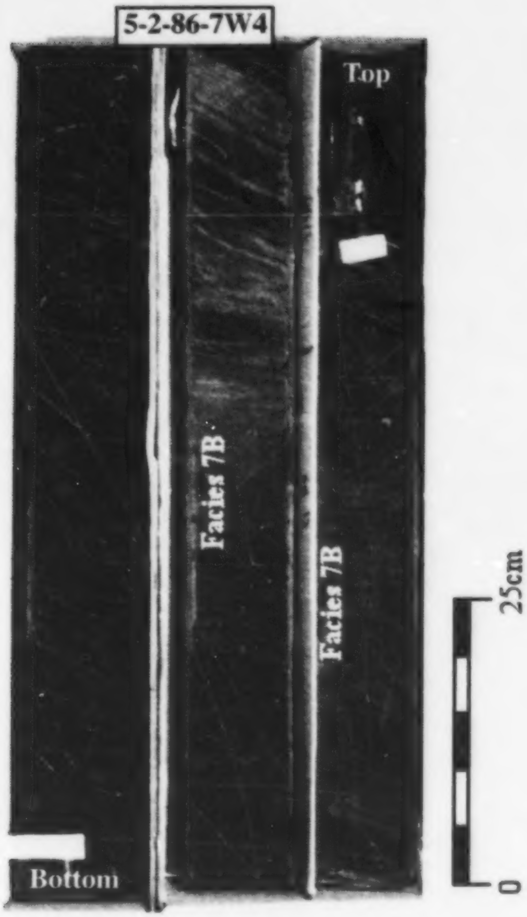

5-2-86-7W4
Top
Facies 7B
Facies 7B
Bottom
25cm
0

Figure 41: Slumped silty mudstone, with synsedimentary folds and faults. Upper McMurrayFormation. Facies 7B.

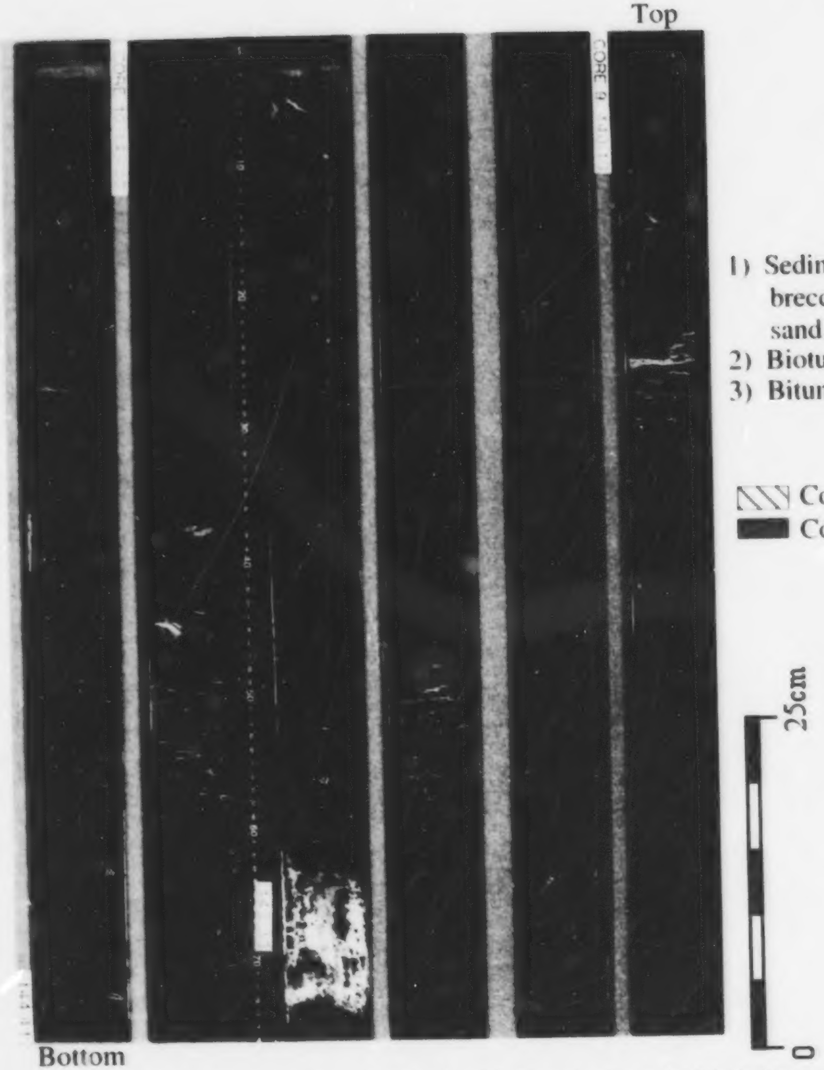
5.8A Facies 8A: Fine to Coarse Grained, Massive Sand

Facies 8A is dominated by fine to coarse grained massive sand that is apparently structureless and is unburrowed. Facies 8A is common in both the Lower McMurray and the Upper McMurray. Intraclasts or coal detritus may be randomly and widely dispersed within the sand. Massive sands average about 1.5 metres thick (Figure 42). The sand is subangular (Lower McMurray) to well rounded (Upper McMurray). Some of the apparently very thick, structureless sand may be incorrectly identified due to very high bitumen saturations that obscure sedimentary features. Often sedimentary structures within oil sand core may be identified by x-raying selected intervals, or by using Magnetic Resonance Imaging (MRI) techniques.

In cases where structureless sands of the Upper McMurray overlie and/or rework massive sands of the Lower McMurray Formation, distinction of the two successions is difficult. If dispersed mudstone clasts are present in the massive sands then bioturbation features in the associated mudstone clasts may be used to identify the sands as Upper McMurray. Otherwise, associated facies and vertical and lateral stratigraphic relationships must be used. Facies 8A often underlies or interfingers laterally with the sandy Facies 1, 2, 5, 6, 7A, and 3 in the Lower and Upper McMurray successions. On the gamma ray log Facies 7A appears as a clean (low gamma ray) sand.

The massive sands have been observed in many outcrops on the Athabasca, Steepbank, Ells, Hangingstone, Horse, Christina and MacKay rivers. Facies 8A is primarily found within the lower portions of both the Lower and Upper McMurray successions, usually associated with other sand-dominated facies.

Interpretation: By more broader facies associations, this facies is interpreted as being deposited from high-energy currents that flowed within channels. These massive sands form part of the normal braided channel flow processes in Lower McMurray time. They also form part of the normal meandering tidal-estuarine channel flows in Upper McMurray time. Facies 8A is a common facies of the lowstand fluvial and transgressive estuarine deposits.



1) Sedimentary Features: mudstone breccia, massive to cross-bedded sand
2) Bioturbation Index: 1
3) Bitumen Saturation: excellent

▨ Cored Interval
■ Core Interval Viewed

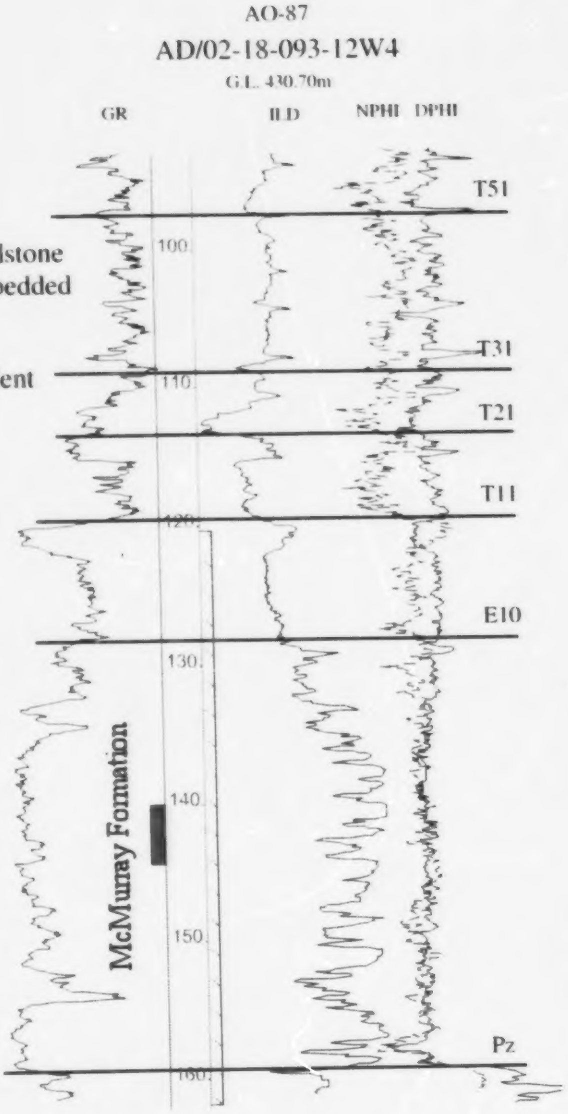


Figure 42: Massive sand interbedded with trough cross-bedded (Facies 5) sand and mudstone-clast breccia (Facies 7A). Upper McMurray Formation. Facies 7B (10B). Geophysical log response shown to the right.

5.8B Facies 8B: Poorly to Well Sorted, Massive Sandy Silt/Silty Sand

Facies 8B is dominated by very fine grained, massive silty sand to silty sand, that is, apparently, structureless and has an unburrowed matrix (Figure 40). Facies 8B is rare in the Lower and Upper McMurray. Less commonly intraclasts or coal detritus may be randomly and widely dispersed within the sand or siltstone. Massive silty sands/sandy silts average about 0.5 metres thick, ranging from about 0.1 to 2.0 metres thick.

Facies 8B is not particularly common within either the Lower or Upper McMurray succession. The massive sandy siltstone facies has been observed in some outcrops on the Athabasca drainage network.

Interpretation: This facies is interpreted as being deposited from current or suspension fallout flows that occupied fluvial and estuarine channels and flowed into overbank settings. These massive sandy siltstones/siltstones forms part of the normal braided channel flow processes in Lower McMurray time, and as part of the normal meandering estuarine-channel flows in Upper McMurray time. Facies 8B is interpreted as one of the rare facies within both the lowstand fluvial and transgressive estuarine deposits.

5.9A Facies 9A: Very Fine to Fine Grained, Ripple Cross Bedded Sand

Facies 9A is ubiquitous throughout the McMurray succession. Facies 9A is common in the Lower and very common in the Upper McMurray sediments. Very fine to fine grained, ripple-cross bedded, quartz-dominated sand characterizes the unit (Figures 43 to 46). Rippled sand beds average about 0.4 metres thick, ranging from wispy lamination < 0.5 centimetre to amalgamated beds up to 4 metres thick. The sand is subangular (Lower McMurray) to well rounded (Upper McMurray) and is most often well sorted. Facies 4 is variably argillaceous ranging from very clean (dominant in the Lower McMurray) (Figures 43, 44) to moderately or highly argillaceous (Upper McMurray) (Figures 46). Amalgamated bed sets may extend over tens of metres laterally (observed in outcrop), and beds most commonly have an erosional top and base. Rare, very thin, discontinuous coal interlaminae and fragments are observed.

In the Lower McMurray Formation Facies 9A is most commonly associated with Facies 2 and 6. In Upper McMurray Formation the rippled sands are common in all parts of the succession from the base to the top. Ripple cross bed types include current ripples and climbing ripples (Figure 43, 45, 46), often in association with low-angle, inclined heterolithic stratification (Figure 43, 45, 46); and, in tidal sediments, bidirectional small scale herringbone cross bedding (Figure 44). Facies 9A is most commonly associated with Facies 5, 6, 10A, 8A, 8B, 9B, 11, 12A, and 15. The rippled sand facies often distinctly separates trough and planar tabular cross bed sets (Figures 32, 33). Although this facies is generally thin and is found interbedded with larger, thicker facies, Facies 9A has been observed as a thick stand alone succession (eg: McMurray type section-Athabasca River).

The very fine to fine grained, ripple-cross bedded sand facies has been observed in virtually all outcrops on the Athabasca, Steepbank, Ells, Hangingstone, Christina and MacKay rivers. In core Facies 9A is recognized by prominent and well-defined ripple or ripple-drift cross bedding and apparent unidirectional paleoflows (Figures 45, 46). Less commonly sands show convolute ripple cross lamination, indicative of rapid sedimentation along with dewatering during deposition, or herringbone cross bedding associated with reversing tidal currents.

Interpretation: This facies is interpreted as being deposited from small-scale three-dimensional sand dunes or current ripples that migrated along the bottoms of sandy channels or on fluvial-tidal- bars. Rippled sands are ubiquitous as: 1) part of the current deposits of the lacustrine units in the Lower McMurray; 2) normal fluvial channel and overbank flood flows throughout the McMurray; 3) flood flows in the vertical accreted abandoned channel fill units; and, 4) part of the normal depositional processes in point bar environments of the channelized portion of the Upper McMurray. In the Upper McMurray, rippled sands are also part of the coastal plain complex. They occur in flood channels, tidal and storm washovers into brackish bays, in deltaic and interdeltaic settings. Because of the ubiquitous nature of rippled sands, they are not diagnostic of any particular environment, but only indicate unidirectional flows that were capable of transporting very fine to fine-grained sand. Facies 9A is interpreted as one of the common facies of the fluvial lowstand deposits and very common within the overlying transgressive deposits of the Upper McMurray.

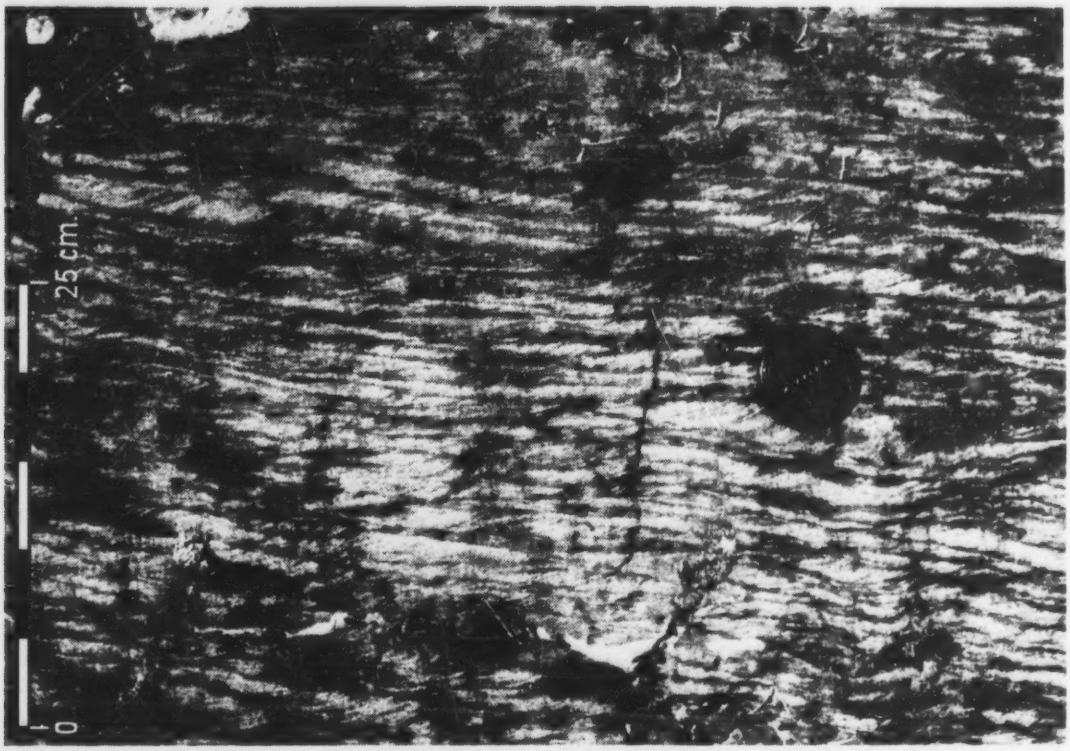


Figure 43: Ripple and ripple-drift cross-bedded sand, Upper McMurray Formation, Viewpoint section, MacKay River. Facies 9A.

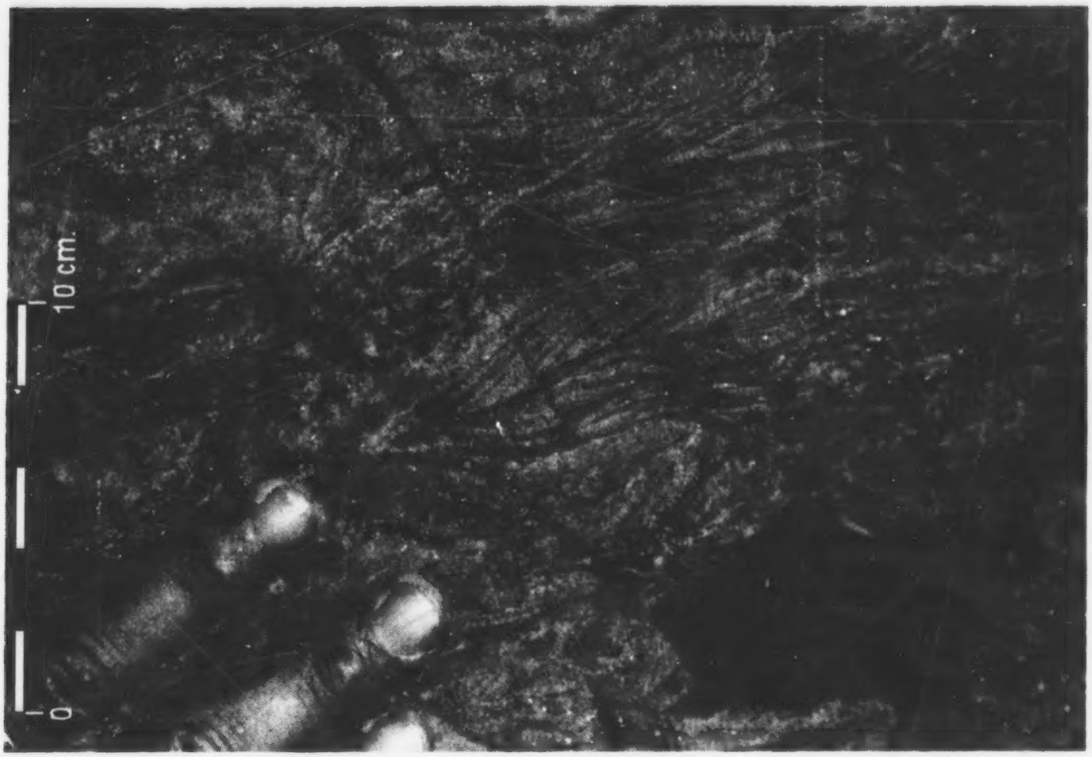
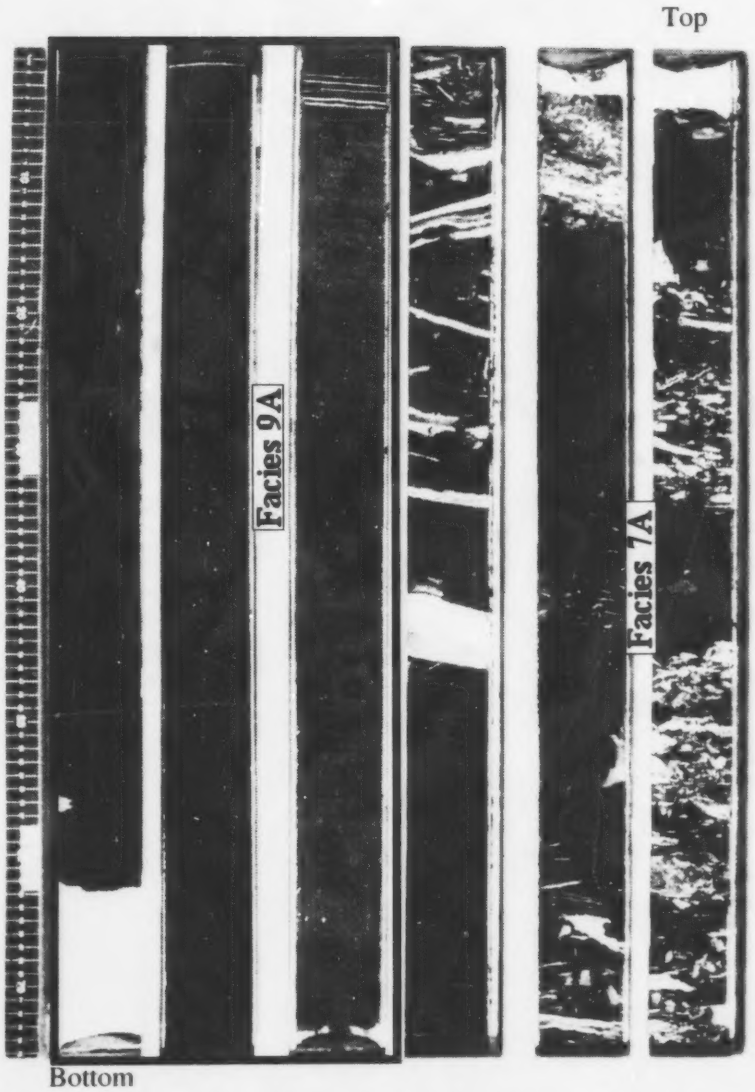


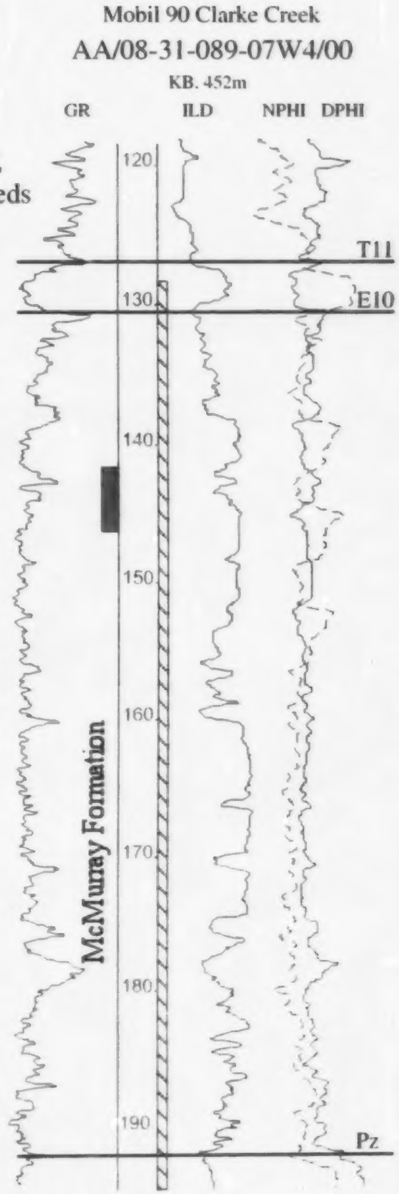
Figure 44: Small-scale herringbone cross-bedding, shown by alternating ripple cross-beds, with minor convolution, Upper McMurray Formation, Horse River. Alternating paleoflows indicative of tidal current reversal. Facies 9A.

Top



1) Sedimentary Features: rippled sand, breccia beds, minor inclined mud beds
2) Bioturbation Index: 2 (clasts)
3) Bitumen Saturation: fair to poor

▨ Cored Interval
■ Core Interval Viewed



Bottom

Figure 45: Rippled sand, overlain by mudstone-clast breccia beds with minor inclined mud beds, Upper McMurray Formation. Facies 9A, (7A, 10A). Geophysical log response shown to the right.

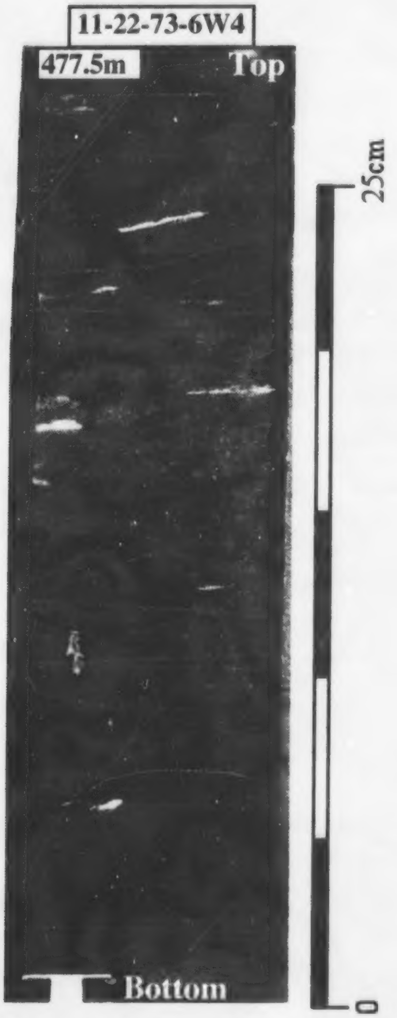

11-22-73-6W4
477.5m
Top
25cm
Bottom
0

Figure 46: Current ripple and ripple drift sand, overlying lateral accretion cross-bedded sand, Upper McMurray Formation. Facies 9A.

5.9B Facies 9B: Very Fine to Fine Grained, Flaser Bedded Sand and Mudstone

Facies 9B is common in the Upper McMurray succession. Very fine to fine grained, well sorted, generally unburrowed, flaser bedded sand and mudstone characterizes this facies (Figures 47 to 49). Facies 9B averages about 0.75 metres thick, ranging from 0.20 to 3 metres thick. The sand is rounded to well rounded and is most often well sorted. This facies differs from Facies 9A in that it is generally finer grained on average, and the prominent interlamination of sand and mud lithologies within the ripple sets.

In core Facies 9B is a relatively common facies recognized by prominent and well defined, 'zebra-like' pinstriping of sand and mud lithologies, with very well defined ripple cross bedding, showing evidence of ripple drift, alternating bidirectional paleoflows, and normal or inverse grading. Bifurcating mudstone interlaminae are common. Facies 9B may alternate with the rippled sands of Facies 9A, or may be associated with other rhythmic tidal deposits, such as Facies 12A, 12B, 12C, 12D, and 12E. A gamma ray profile generally shows a muddy sand pattern (Figure 49).

As with other muddy facies within the Upper McMurray succession Facies 9B is not a commonly occurring facies in outcrop. Rare occurrences have been observed on the Ells, Christina and Athabasca rivers.

Interpretation: This facies is interpreted as being deposited from bi- and unidirectional currents along with suspension fallout in tidal flat and tidal channel complexes, now preserved as estuarine deposits of the Upper McMurray Formation. The environment where this facies is preserved generally lacks bioturbation features, indicative of high sedimentation rates. Most likely settings are within the mud-line of subtidal channels; protected bays; or abandoned channels/sloughs in the coastal plain/tidal flat environment. Facies 9B is interpreted as one of the common facies of transgressive estuarine deposits, in tidal settings with regularly fluctuating currents.

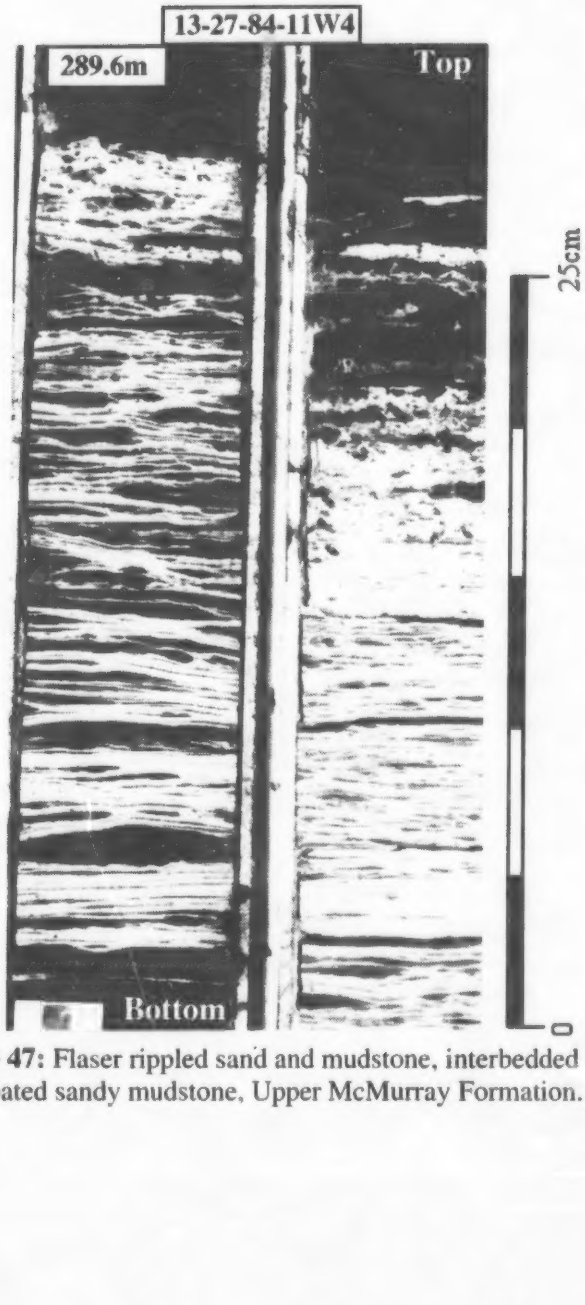

13-27-84-11W4
289.6m
Top
Bottom
25cm
0

Figure 47: Flaser rippled sand and mudstone, interbedded with bioturbated sandy mudstone, Upper McMurray Formation. Facies 9B.

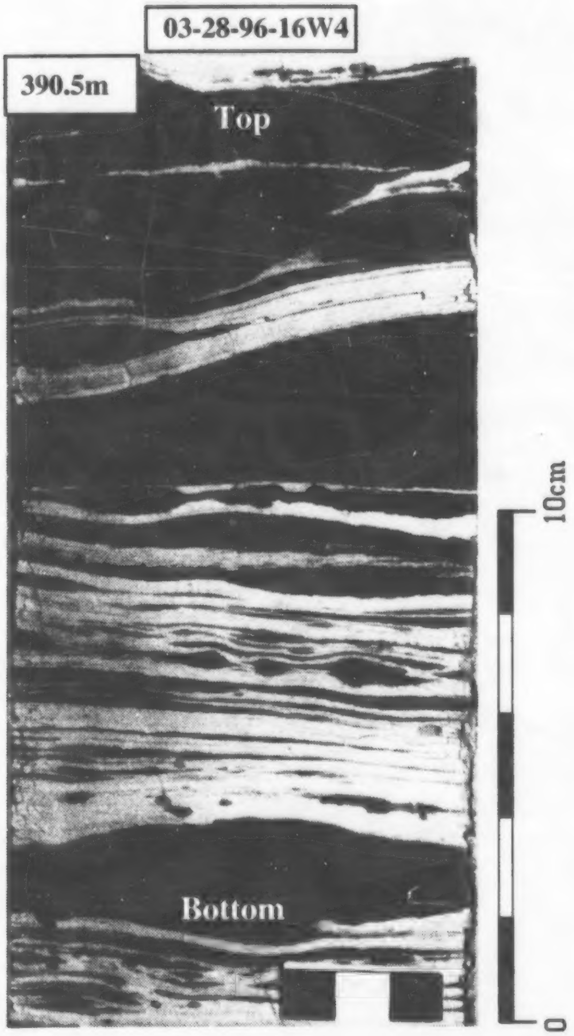
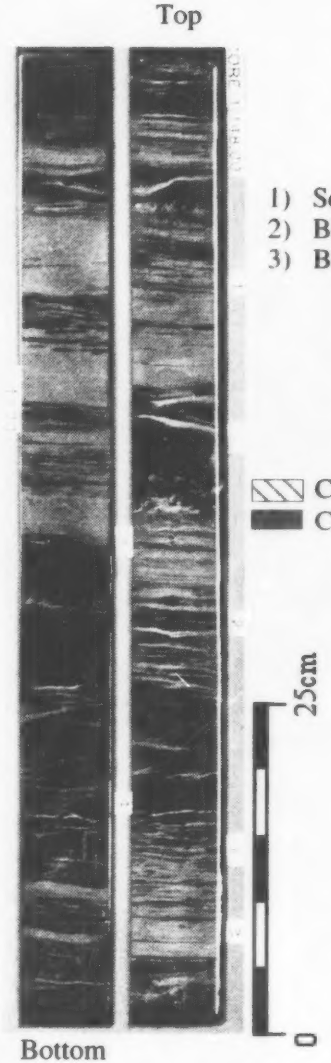

03-28-96-16W4
390.5m
Top
Bottom
10cm
0

Figure 48: Wave-ripples or combined-flow features in the upper half of the photograph, interbedded with flaser rippled sand and mudstone, Upper McMurray Formation. Facies 9B, 16.



1) Sedimentary Features: flaser bedded, rythmically laminated
2) Bioturbation Index: 2
3) Bitumen Saturation: fair

▨ Cored Interval
■ Core Interval Viewed

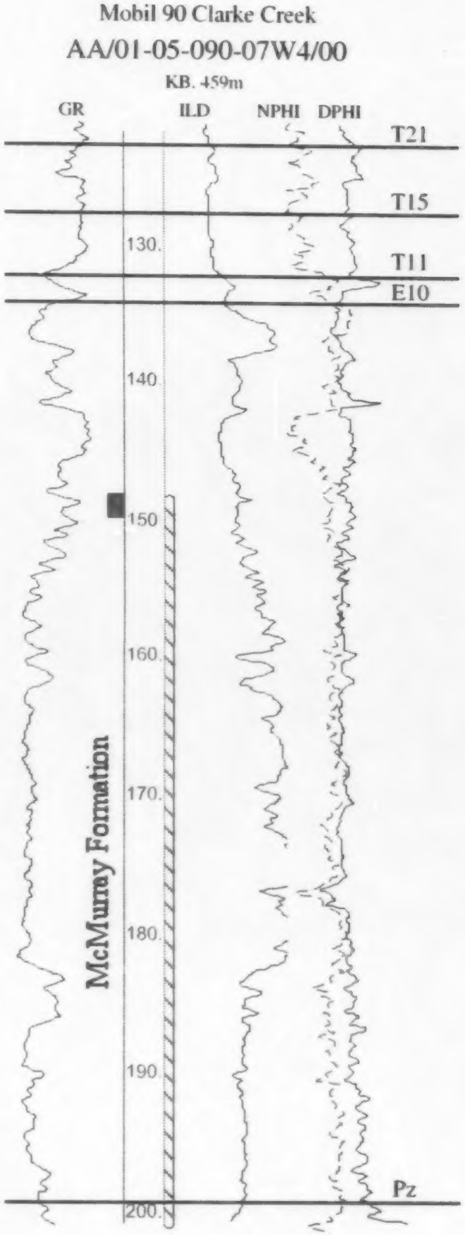


Figure 49: Flaser-bedded and interbedded sand and mudstone, Upper McMurray Formation. Facies 9B, 12A. Geophysical log response shown to the right.

5.10A Facies 10A: Bioturbated, Inclined Heterolithic Stratified Muddy Sand

Facies 10A is a sand-dominated unit comprised of medium scale, interbedded sand and mudstone units that have moderate to abundant bioturbation. Facies 10A is very common in the Upper McMurray Formation. Very fine to fine grained, low-angle inclined, quartz-dominated rippled, massive or laminated sand, separated by burrowed, muddy interlaminae, characterizes the unit (Figures 50 to 54). Inclined heterolithic stratified sand units average about 3.0 metres thick, ranging from 1.0 metre to greater than 15 metres thick (Figures 50, 51). The sand is well rounded and is most often well sorted. Facies 10A is variably argillaceous ranging from moderately to highly argillaceous. Packages of inclined heterolithic sets generally from range tens of metres to greater than 100 metres in lateral extent; and, have a transitional or sharp base, and generally a transitional top. Bedding inclination generally ranges from 5 to 10 degrees. Individual sand beds within the inclined heterolithic succession average about 0.3 metres thick, are dominated by ripple, ripple-drift or flaser cross bedding, and show variable degrees of bioturbation (Figures 52-54). Within the Upper McMurray Formation mudstone beds separating the sand beds are generally 3 to 10 cm thick, moderately to heavily burrowed and have irregular, burrowed, contacts with adjacent sand beds. The mud content within Facies 10A often increases upward within the succession. In the Upper McMurray Formation the common trace fossils within the inclined heterolithic stratified units include *Cylindrichnus* and *Planolites*. Rare, very thin, discontinuous coal interlaminae and detritus have been observed in both core and outcrop (Figure 52).

Facies 10A is often associated with Facies 10B, 1, 6, 9A, 9B, 12, 13 and 14 in sediments of the Upper McMurray. In the gamma ray log Facies 10A typically appears as a muddy, fining upward unit transitionally capping relatively thick, clean, blocky sand (140 – 158 m depth Figure 54). Facies 10A often grades upwards into heavily burrowed sandy and silty mudstones. Within some regions of the Athabasca area where repeated erosion and depositional cycles occur identification of this facies is more problematic.

The very fine to fine grained, inclined heterolithic sand facies has been observed in virtually all outcrops on the Athabasca, Steepbank, Ells, Hangingstone, Christina and MacKay rivers. In core Facies 10A is recognized by prominent and well-defined, thin, low-angle mudstone beds. Less commonly sands show convoluted-cross lamination, indicative of rapid sedimentation along with dewatering during deposition.

Interpretation: This facies is interpreted as being deposited from mainly unidirectional flow currents and suspension fallout that occurred on point bars within meandering fluvial- or estuarine-dominated channels. These inclined heterolithic sands are part of the normal depositional processes in point bar environments of the Upper McMurray succession.

pre-Cretaceous unconformity

Figure 50: Large scale, inclined heterolithic stratification, showing alternating dip direction, Upper McMurray Formation, Outcrop #3, Steepbank River. Approximate height of outcrop is 35 m. Facies 10A.

Figure 51: Massive to parallel bedded units at base (Facies 5, 8A) overlain by large scale lateral accretion cross-beds (Facies 10A), Horse River. Facies 10A, 8A and 5.

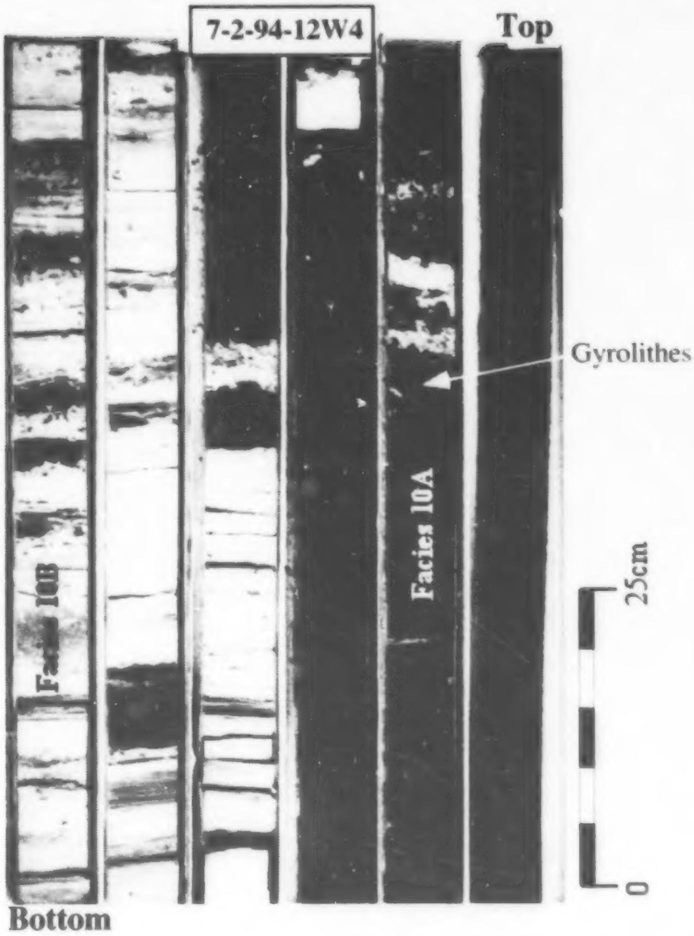

7-2-94-12W4
Top
Gyrolithes
Facies 10A
Facies 10B
25cm
0
Bottom

Figure 52: Very fine to fine grained, bioturbated, sand-dominated, inclined heterolithic stratification (IHS) with coal debris (Facies 10A), overlying bioturbated, mud-dominated inclined heterolithic stratification (IHS)(Facies 10B), Upper McMurray Formation. Facies 10A and 10B.

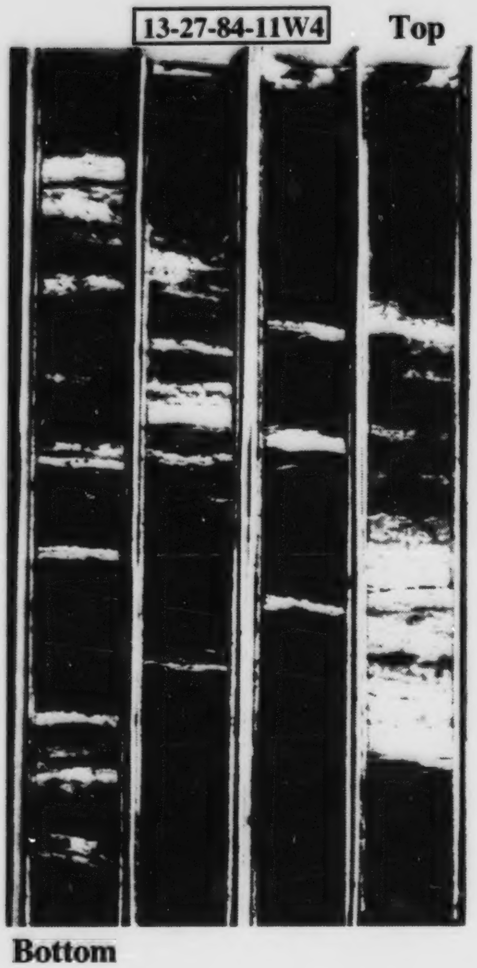

13-27-84-11W4
Top
Bottom

Figure 53: Very fine to fine grained, bioturbated, sand-dominated, inclined heterolithic stratification with minor flaser ripples at the base, Upper McMurray Formation. Facies 10A.

72

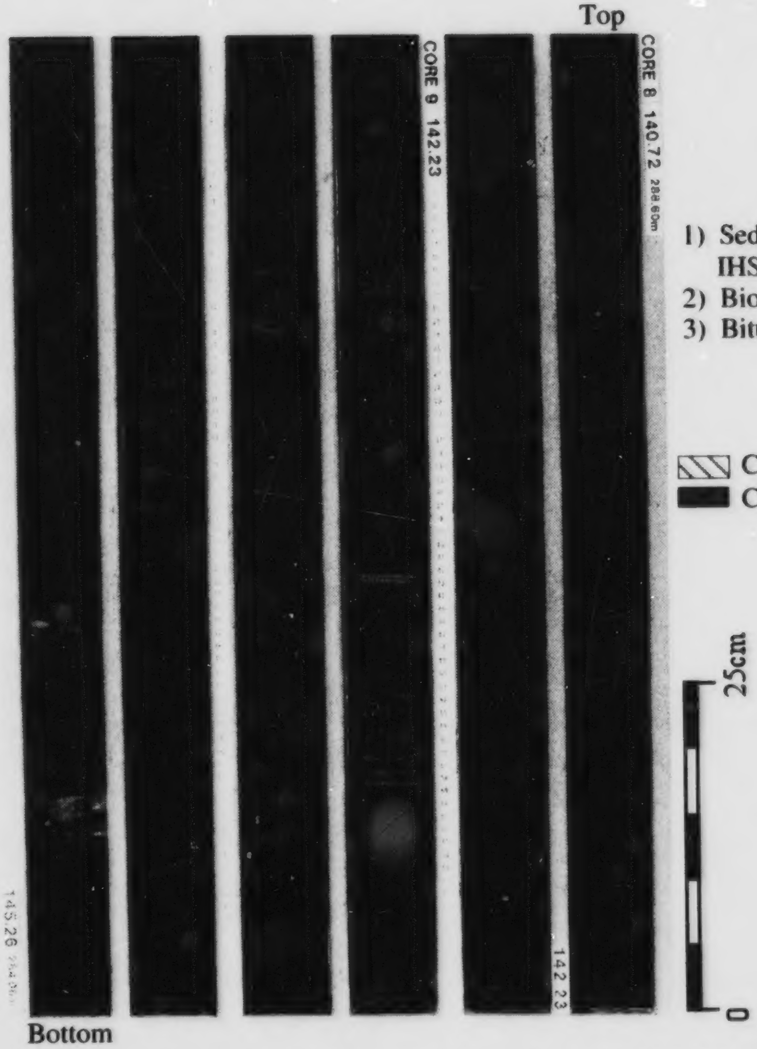
5.10B Facies 10B: Bioturbated, Inclined Heterolithic Stratified Sandy Mudstone

Facies 10B comprises mudstone-dominated, inclined heterolithic stratification and is moderately to highly burrowed. Facies 10B is less common than Facies 10A and is generally confined to the Upper McMurray succession. Low angle (5 to 10 degrees), inclined mudstone and sandy mudstone, interbedded with fine to very fine grained, rippled, massive or laminated sand characterizes the unit (Figures 55 to 58). Single sets of inclined heterolithic stratified mudstone average about 2 metre thick, ranging from 1.0 metre to over 5 metres thick. The sand component is well rounded and is most often well sorted. Mudstone-sand contacts are irregular primarily due to bioturbation. Inclined heterolithic sets generally range from tens metres to well over 100 metres in lateral extent; have a transitional or sharp base; and commonly a transitional top. Rare, very thin, discontinuous coal interlaminae are sometimes present. Facies 10B units may overlie or interfinger laterally with the inclined heterolithic sand of Facies 10A.

Facies 10B is relatively common throughout the Upper McMurray succession. The mudstone-dominated inclined heterolithic stratified facies is often associated with Facies 9A, 9B, 10A and various muddy subfacies within Facies 12. A gamma ray profile shows a curve similar to that of Facies 10A of a well-defined curve displaying a fining-upward succession that often caps cleaner, blocky sands (Figure 58). The curve shows the mud-dominant lithologies by a shift to the right (increased radioactivity) compared to Facies 10A (Figure 54, 58).

The inclined heterolithic sandy mudstone facies has been rarely observed in outcrop. Limited exposures have been observed along the Ells and MacKay rivers. In core Facies 10B is recognized by mudstone with prominent and well defined low-angle bedding, with thin sand interbeds and the apparent unidirectional paleoflows along apparent bedding trends. Common trace fossils include *Cylindrichnus*, *Planolites* and rare *Gyrolithes*.

Interpretation: This facies is interpreted as being deposited from unidirectional flow currents and suspension fallout that occurred along the margins of point bars within small-scale, secondary muddy meandering estuarine/tidal channels. These inclined heterolithic sandy mudstones form part of the current deposits and overbank flood flows in Upper McMurray time in estuarine or tidal point bar settings. These particular deposits may also indicate the initial stages of estuarine channel abandonment when the main channel flow is being diverted elsewhere limiting the amount of sand input into the channel being abandoned with the exception of flood events. Facies 10B likely forms a major component of vertical-accretion channel-fill successions in the region. Facies 10B is one of the common facies of the transgressive estuarine deposits.


Top
CORE 8 140.72 288.60m
142.23
CORE 9 142.23
145.26
Bottom
25cm
0

1) Sedimentary features: mud flasers, IHS, rippled sand
2) Bioturbation Index: 2
3) Bitumen Saturation: very good

▨ Cored Interval
■ Core Interval Viewed

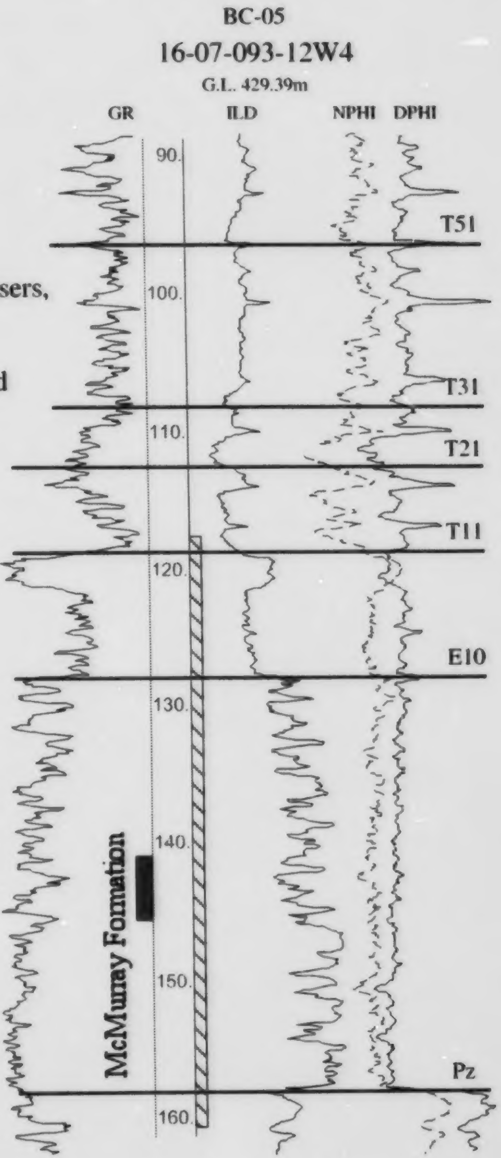


Figure 54: Moderately bioturbated, sand-dominated, inclined heterolithic stratification, Upper McMurray Formation. Facies 10A. Geophysical log response shown to the right.

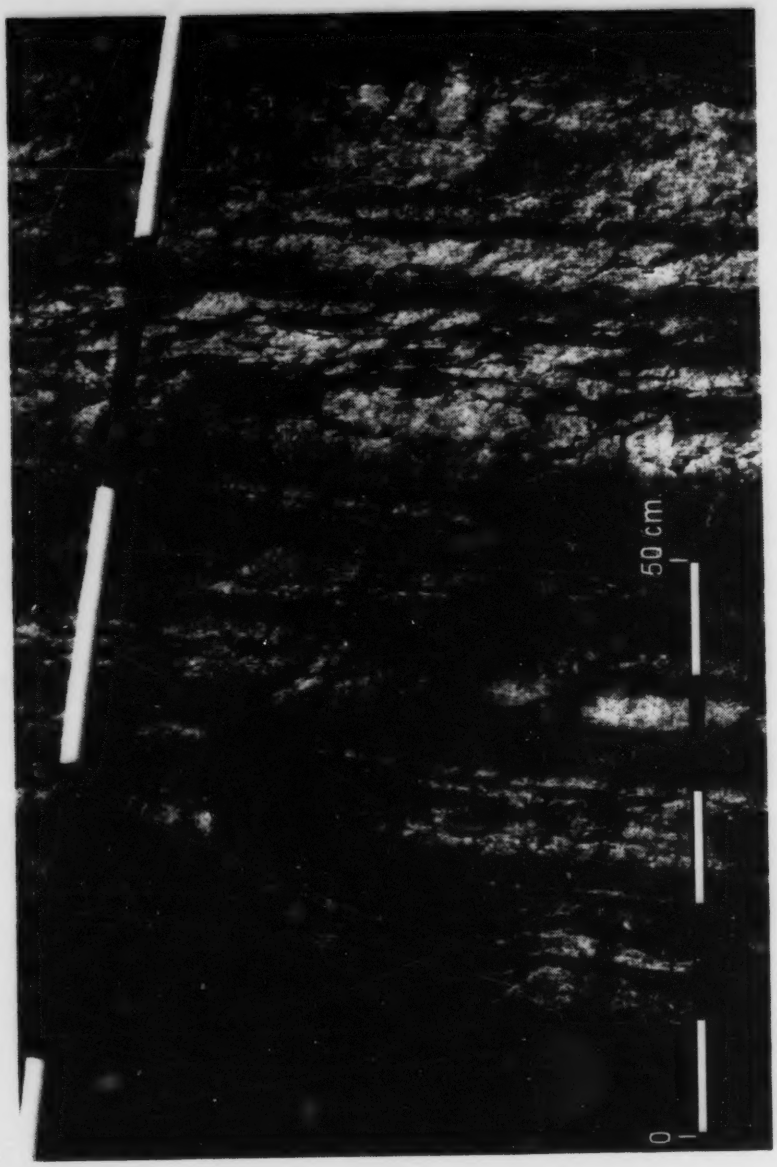


Figure 55: Bioturbated, mud-dominated, inclined heterolithic stratification, upper part of an estuarine point bar succession, Upper McMurray Formation, type section of the McMurray Formation on the Athabasca River. Facies 10B.

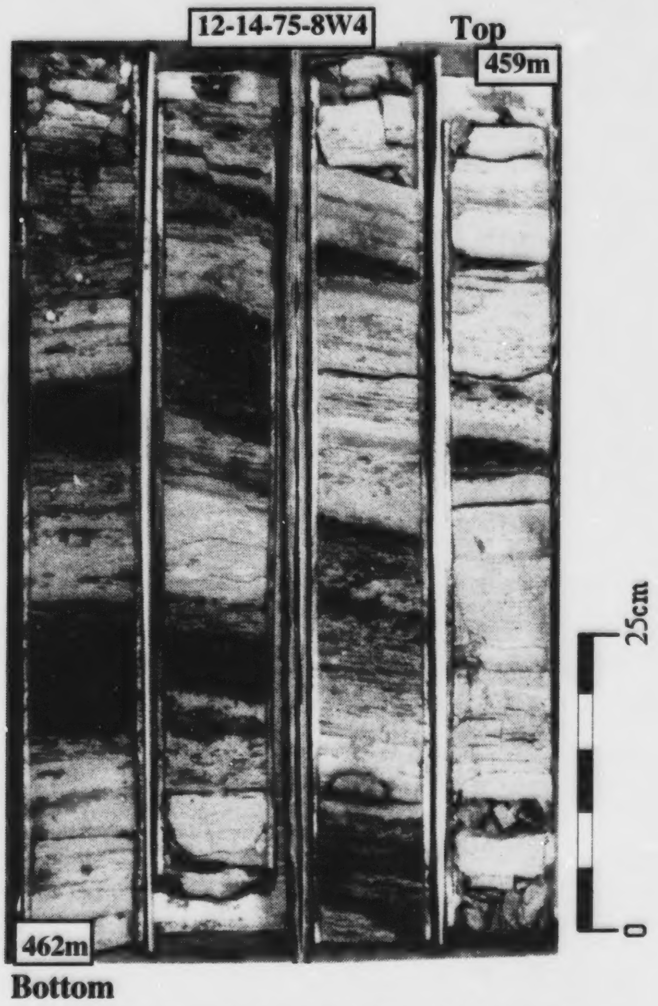

12-14-75-8W4
Top
459m
462m
Bottom
25cm
0

Figure 56: Moderately bioturbated, mud-dominated, inclined heterolithic stratification, upper part of an estuarine point bar succession, Upper McMurray Formation. Facies 10B.

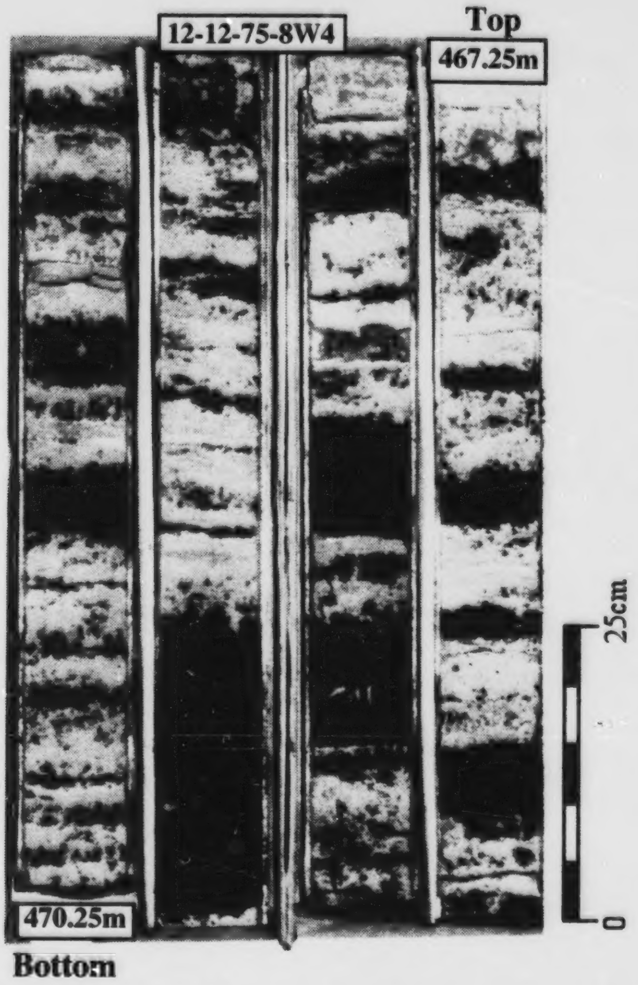
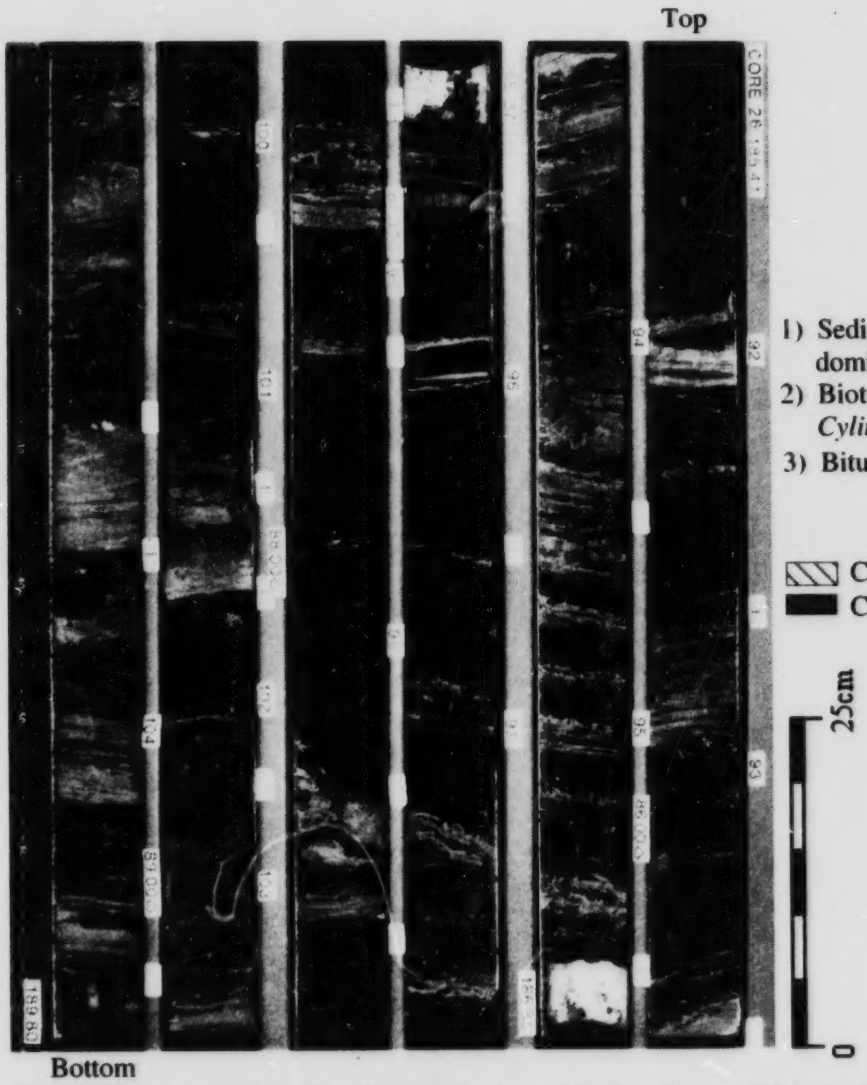

12-12-75-8W4
Top
467.25m
25cm
0
470.25m
Bottom

Figure 57: Heavily bioturbated, mud-dominated, inclined heterolithic stratification, Upper McMurray Formation. Facies 10B. (Note abundant *Gyrolithes* burrowing).


Top
CORE 26 185.41
92
93
94
95
96
100
101
102
103
104
189.80
Bottom
25cm
0

1) Sedimentary Features: mud dominated IHS, mud flasers
2) Bioturbation Index: 3-5 *Cylindrichus* and *Planolites*
3) Bitumen Saturation: fair to good

▨ Cored Interval
■ Core Interval Viewed

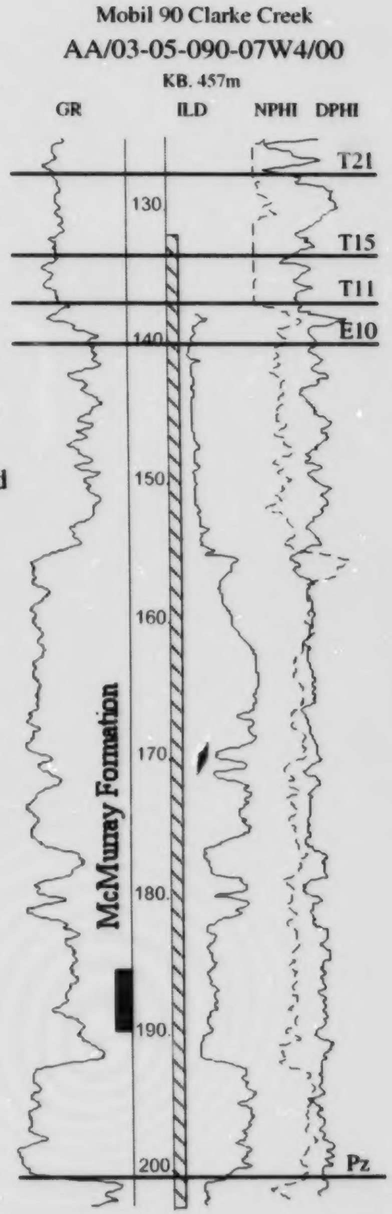


Figure 58: Heavily bioturbated, mud-dominated, inclined heterolithic stratification, minor flaser-ripple cross-bedding, Upper McMurray Formation. Facies 10B (9B). Geophysical log response shown to the right

5.11 Facies 11: Very Fine to Medium Grained, Stratified Sand

Facies 11 is one of the rare facies within the McMurray Formation. The lithological unit is present in the Lower McMurray but is best represented in the Upper McMurray Formation (Figure 59). Very fine to medium grained, clean, planar laminated sand, with rare traces (mainly *Skolithos*), characterizes this facies. Units of this facies average about 0.5 metres thick, ranging from < 0.2 to 2 metres thick.

In the Lower McMurray, the sand is subangular to subrounded and is most often moderately well sorted; whereas, in the Upper McMurray the sand is rounded to well rounded, and well to very well sorted. Horizontally stratified sand beds have an erosional base, and a more gradational top, and often alternates with or is capped by well defined current ripples or ripple-drift cross lamination (Facies 9A) (Figure 59). The unit sometimes contains thin, discontinuous interbeds of light grey silty mudstone, or carbonaceous mudstone near the top of stratified sand units. Rare vertical *Skolithos* burrows occur in the sands of this facies.

Facies 11 is limited vertically and laterally in both the Lower and Upper McMurray successions. The planar stratified unit is commonly associated with Facies 1, 2 and 6 in the Lower McMurray and most of the facies within the Upper McMurray.

The very fine to medium grained, horizontally stratified sand facies has been observed in some outcrops along the Athabasca drainage network. In core, Facies 11 is recognized by prominent and well-defined horizontal stratification.

Interpretation: This facies is interpreted as being deposited from high energy upper flow regime currents that migrated along the bottoms of river or tidal-estuarine channels, where high flood flow events overtopped channels and inundated river or tidal bars, or were storm washover events that flooded coastal plain settings. In all cases this facies is indicative of high-energy events that occurred in fluvial, tidal or coastal settings. Facies 12 is interpreted as one of the less commonly preserved facies in the fluvial-dominated lowstand deposits, and somewhat more common within the estuarine-dominated transgressive deposits.

05-02-86-07W4
Top
Facies 9A
Facies 9A
Facies 11
188.8m
Bottom
10cm
0

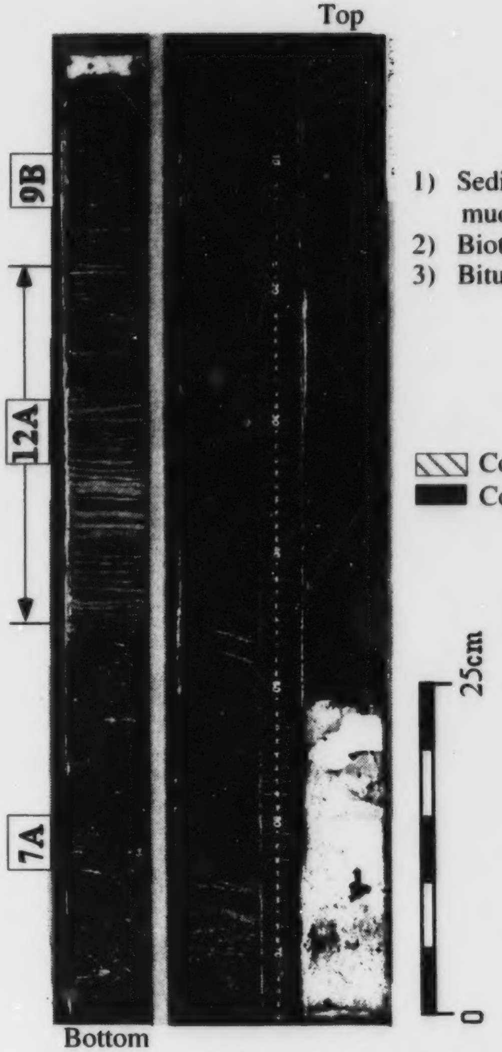
Figure 59: Ripple-drift cross bedded sand (Facies 9A), capping horizontally stratified, very fine to fine grained sand (Facies 11), Upper McMurray Formation. Facies 9A and 11.

5.12A Facies 12A: Rhythmically Laminated Sand and Mudstone

Facies 12A is a rare lithological unit generally confined to the Upper McMurray. Very fine to fine grained, quartz-dominated sand is rhythmically interlaminated to very thinly interbedded with light to medium grey mudstone (Figures 60, 61). Rare horizontal bioturbation may be present (*Planolites*) (Figures 60, 61). This facies averages about 2.0 metres thick, ranging from 0.2 m to amalgamated units exceeding 3 m. The sand is rounded to well rounded and is most often well sorted. Sand-mudstone contacts are razor sharp and undulatory.

The unit is usually limited in both vertical and lateral extent (vertical succession < 5 metres). In core Facies 12A is recognized by prominent and well defined, 'zebra-like' pinstriping of sand and mud lithologies, with very well defined stratification features, showing evidence of normal and inverse grading. Sand and mudstone interbed contacts are wavy or horizontal and 'razor-sharp.' Bifurcating mudstone laminae are common. Facies 12A is commonly associated with mudstone-clast breccia (Figure 7A), or less commonly alternates with the rippled sands (Facies 9A). A gamma ray profile displays a serrated mud-dominated curve (Figures 60, 61).
As with most of the facies containing significant amounts of mudstone (or that are mudstone-dominated), Facies 12A is not well represented in outcrop in the Athabasca area.

Interpretation: This facies is interpreted as being deposited from suspension fallout and less commonly current washovers in tidal flat complexes, now preserved as tidal-estuarine deposits of the Upper McMurray Formation. The environment where this facies is preserved lacks prominent bioturbation features, indicative of either very high sedimentation rates, or alternatively dysaerobic/anaerobic conditions. The two most likely possibilities are within the mud-line of subtidal channels, with very high rates of sediment deposition; or, within ponded, decaying, anaerobic bays or abandoned channels or sloughs in the coastal plain or tidal flat environment. The association of rhythmic bedded sand and mudstone interbedded with the mudstone clast breccias is a good example of autocyclic, repetitive cycles of erosion and deposition. Facies 12A may also be indicative of a seaward push from the fluvially dominated end of the estuary that moves the salt wedge seaward. Tidal effects still influence the region as shown by rhythmic bedded sand and mudstone, but salinities may be too low for brackish ichnofauna to establish. Facies 12A is interpreted as one of the rare facies of the transgressive estuarine deposits.



1) Sedimentary Features: laminated sand/mud, mud flasers
2) Bioturbation Index: 1-2
3) Bitumen Saturation: good

▨ Cored Interval
■ Core Interval Viewed

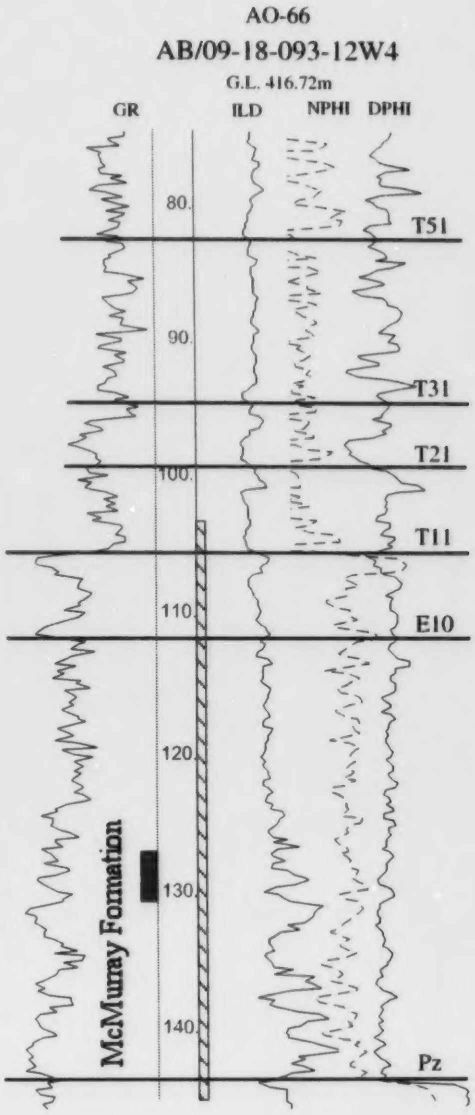
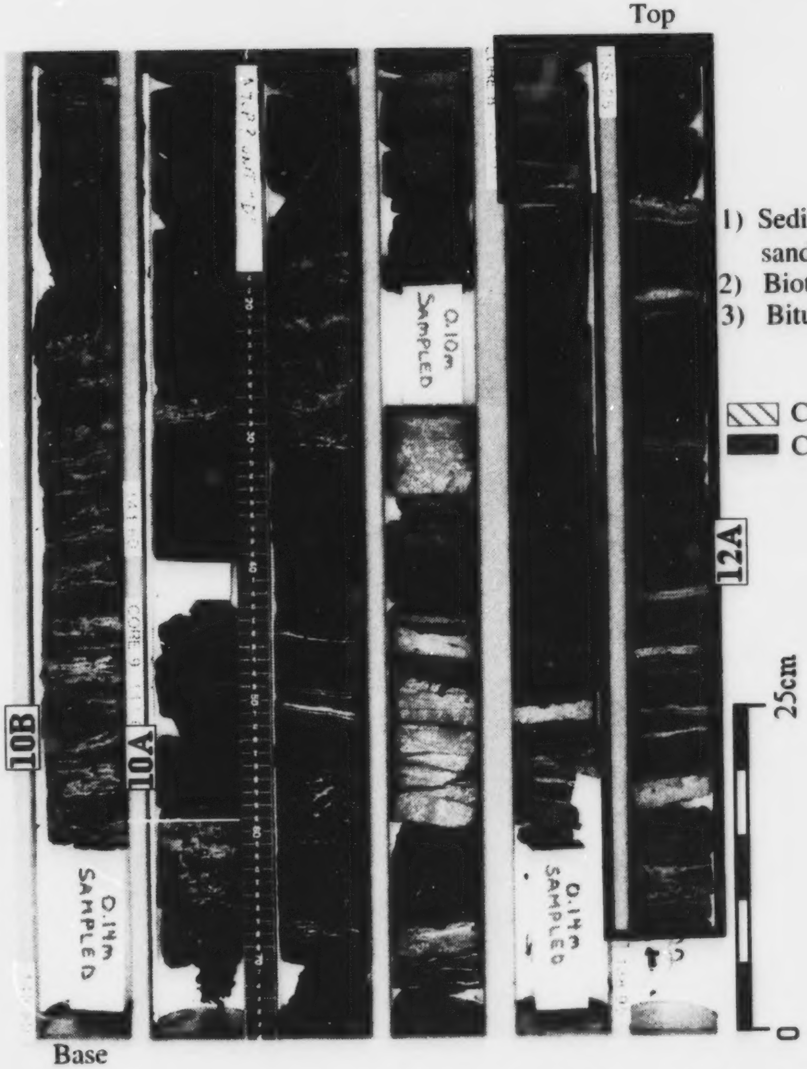


Figure 60: Rhythmically laminated/thinly interbedded, very fine to fine grained sand and mudstone (Facies 12A), interbedded with flaser-rippled sand and mudstone (Facies 9B), Upper McMurray Formation. Geophysical log response shown to the right.


Top
Base
10B
10A
12A
0.14m SAMPLED
0.10m SAMPLED
0.14m SAMPLED
CORE 9
25cm
0

1) Sedimentary Features: laminated sand/mud
2) Bioturbation Index: 2-4
3) Bitumen Saturation: fair

▨ Cored Interval
■ Core Interval Viewed

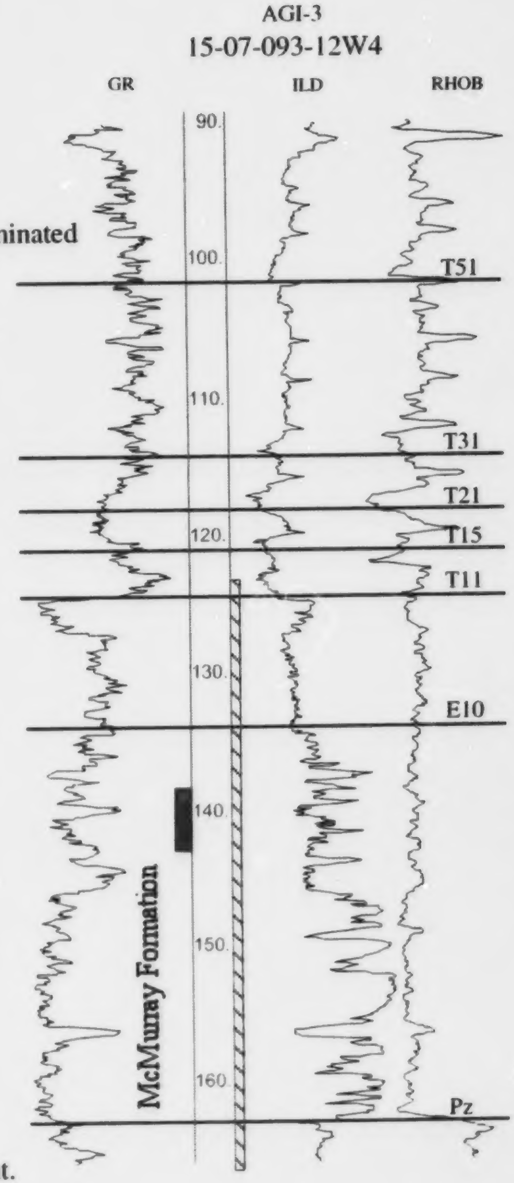


Figure 61a: Rhythmically laminated/thinly interbedded, very fine sand and mudstone (Facies 12A), overlying mud-to-sand dominated, bioturbated inclined heterolithic strata, Upper McMurray Formation. Facies 10A, 10B. Geophysical log response shown to the right.

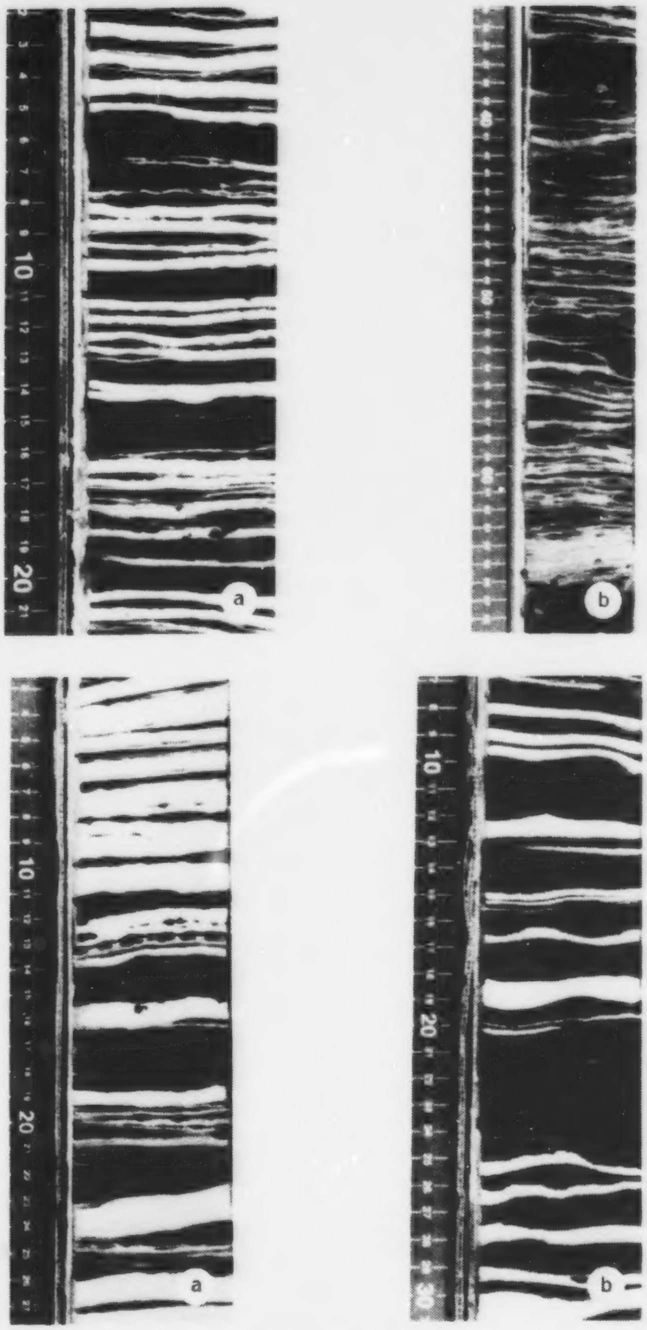


Figure 61b: Rhythmically laminated to very thinly interbedded rippled sand and mudstone. Sharp sand-mudstone contacts, wavy, sometimes inclined bedding. Flaser bedding prominant in upper right photo. Facies 12B. Core is from Township 93, Range 12W4. Vertical scale bar is in cm.

Figure 61c: Rhythmically, wavy laminated to interbedded sand and mudstone with delicate, bifurcating mud laminae, commonly associated mudstone clast breccia. Facies 12B. Core from Township 93, Range 12W4

5.12B Facies 12B: Very Fine to Fine Grained, Bioturbated, Muddy Sand

Facies 12B is common in the Upper McMurray Formation. Very fine to fine grained, well sorted, sand is interlaminated to interbedded with mudstone, with moderate to high bioturbation (Figures 62, 63). The facies averages about 2.0 metres thick, ranging from about 0.20 to 5 metres. The sand is rounded to well rounded and is most often well sorted. This facies differs from Facies 12A in that it has moderate to high degrees of bioturbation and lacks the rhythmic style of interlamination or interbedding.

Sand and mudstone contacts range from sharp to gradational and irregular, generally being admixed or 'blurred' through bioturbation. Primary stratification is preserved in part, while in other portions of interbeds the primary features are totally obscured and obliterated through bioturbation (Figure 63).

In core Facies 12B is recognized by prominent interbedding of sand and mud lithologies, with reasonably defined stratification features, showing evidence of normal and inverse grading, with moderate to high degree of bioturbation (Figure 63). *Cylindrichnus* and *Planolites*, with less common *Teichichnus* and *Skolithos*, dominate the trace fossils. Facies 12B, may alternate with the rippled sands of Facies 9A. This muddy sandstone of Facies 12B grades both vertically and laterally into the sandy mudstone of Facies 12C.

As with other muddy facies within the Upper McMurray succession Facies 12B is not a commonly occurring facies in outcrop.

Interpretation: This facies is interpreted as being deposited from mainly suspension fallout and in tidal flat and channel abandonment fill, now preserved as estuarine deposits within the Upper McMurray Formation. The environment where this facies is preserved has moderate to abundant bioturbation, indicative of either lower sedimentation rates, or alternatively more aerobic conditions. The two most likely locations for the development of this fine-grained, rhythmically laminated and bioturbated muddy sand are as initial stages of channel abandonment within sandy subtidal estuarine or tidal channels. Facies 12B is interpreted as one of the relatively common facies of the transgressive estuarine deposits of the Upper McMurray Formation.

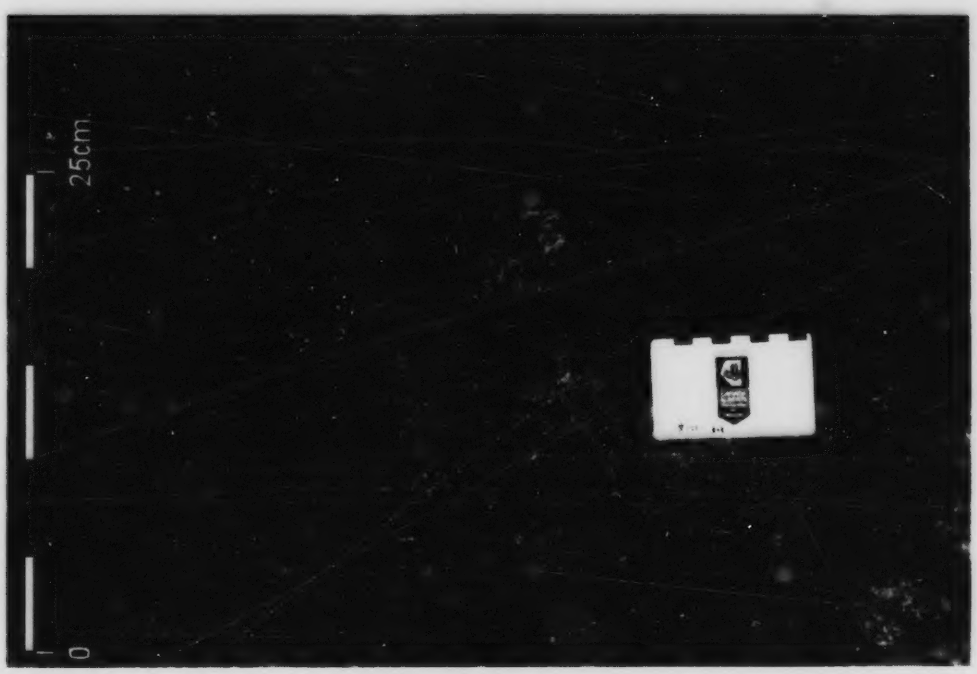
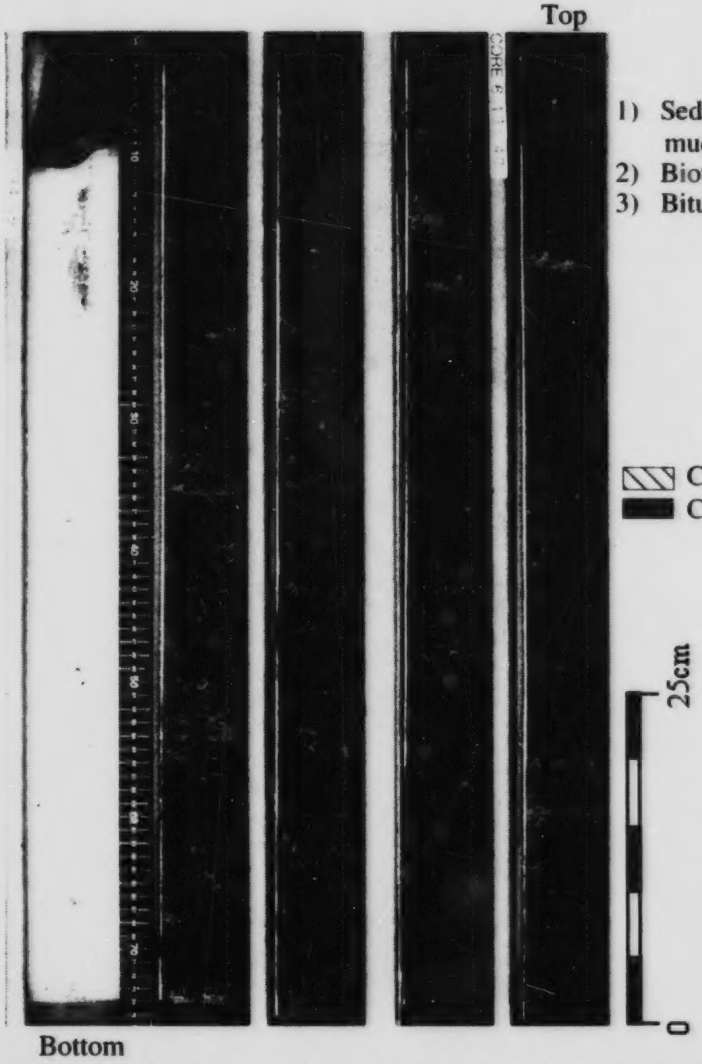


Figure 62: Heavily bioturbated laminated to thinly interbedded muddy sand, Upper McMurray Formation, Outcrop #3, Steepbank River. Facies 12B.



1) Sedimentary Features: burrowed muddy sand, mud flasers
2) Bioturbation Index: 4
3) Bitumen Saturation: fair

▨ Cored Interval
■ Core Interval Viewed

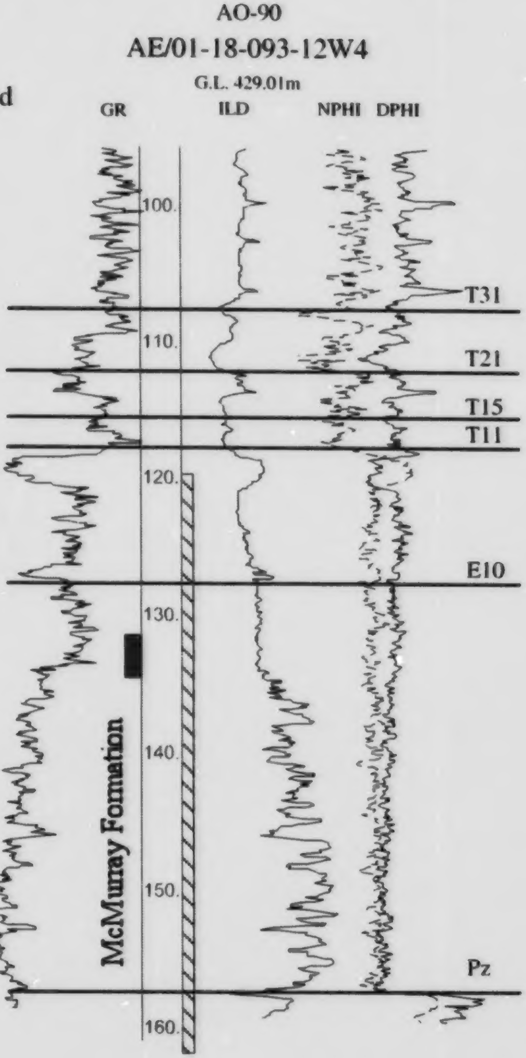


Figure 63: Heavily bioturbated, laminated/thinly interbedded, muddy sand and mudstone (Facies 12B), with minor flaser interbeds (Facies 9B), Upper McMurray Formation. Facies 12B, 9B. Geophysical log response shown to the right.

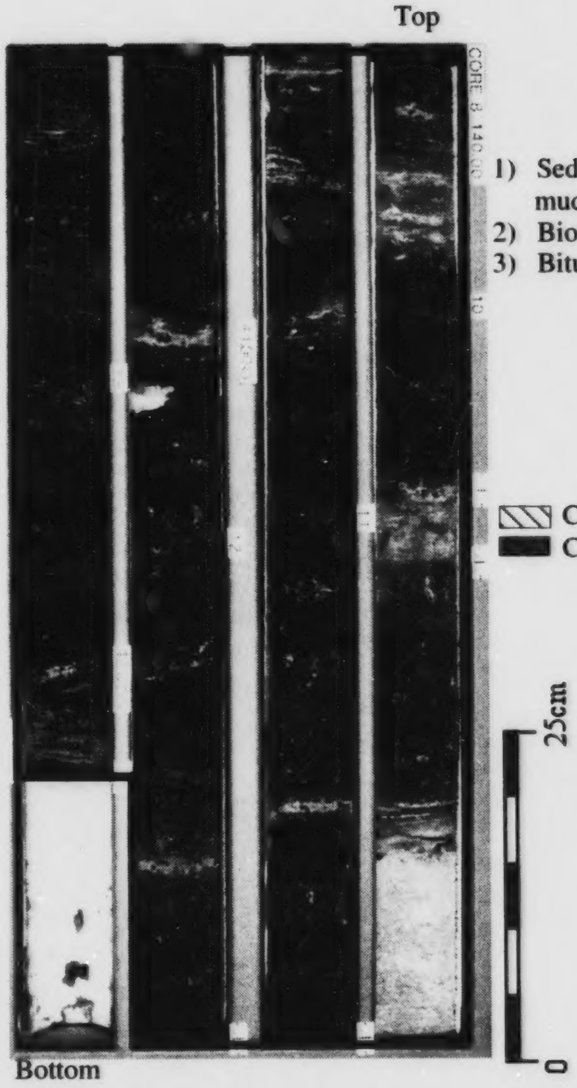
5.12C Facies 12C: Very Fine to Fine Grained, Bioturbated, Sandy Mudstone

Facies 12C is generally confined to the Upper McMurray succession. Very fine grained, well-sorted, sand is an accessory interlaminated component of this mudstone-dominated unit (Figure 64). This facies averages about 2.0 metres thick, ranging from 0.20 metres to 5 metres. The sand is rounded to well rounded and is most often well sorted. Similar to Facies 12B, primary stratification comprised of mudstone and sand are preserved in part, while in some interbeds significant portions may be obliterated through bioturbation.

This muddy facies is most prominent within the middle and upper portions of the Upper McMurray succession. Facies 12C, may alternate with the rippled sands of Facies 9A and 9B, may grade up or downsection into Facies 12B.

The interbedded sandy mudstone facies has been observed in the Ells and MacKay rivers. The unit is usually limited in both vertical and lateral extent. In core, Facies 12C is recognized by the interbedding of sand and mud lithologies, showing evidence of normal and inverse grading, with moderate to high bioturbation.

Interpretation: This facies is interpreted as being deposited from mainly suspension fallout and less commonly current washovers in tidal flat complexes, now preserved as tidal-estuarine deposits of the Upper McMurray Formation. The environment where this facies is preserved has moderate to abundant bioturbation features, indicative slow, continuous deposition without significant erosion. The two most likely possibilities are abandonment fill deposits within estuarine channels or tidal flat environments. Facies 12C is interpreted as one of the relatively common facies of the transgressive estuarine deposits. Paleogeographically Facies 12C is important because of the clear indications of suspension-fallout under lower rates sedimentation rates and oxygenated conditions.



1) Sedimentary Features: some preserved muddy laminations
2) Bioturbation Index: 4
3) Bitumen Saturation: poor to fair

▨ Cored Interval
■ Core Interval Viewed

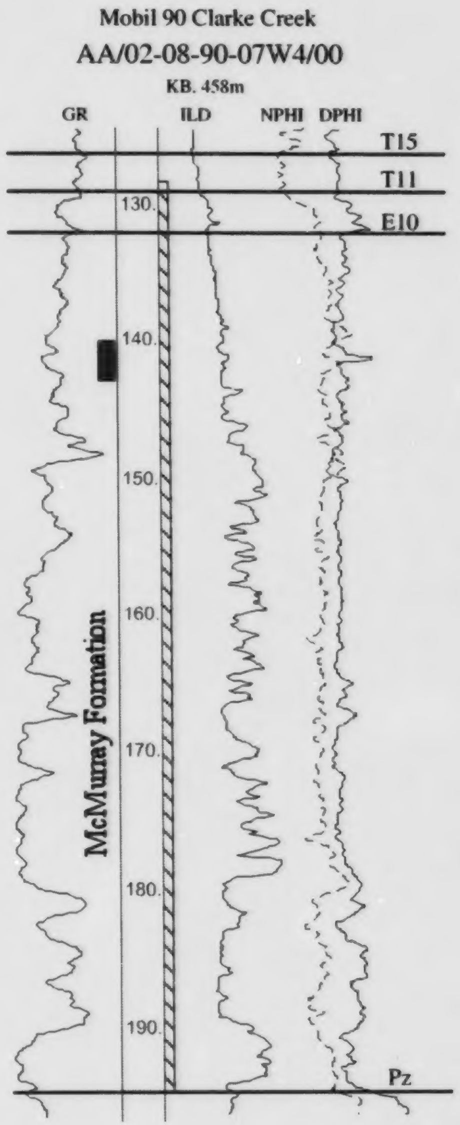


Figure 64: Heavily bioturbated, laminated/thinly interbedded, sandy mud, Upper McMurray Formation. Facies 12C. Geophysical log response shown to the right.

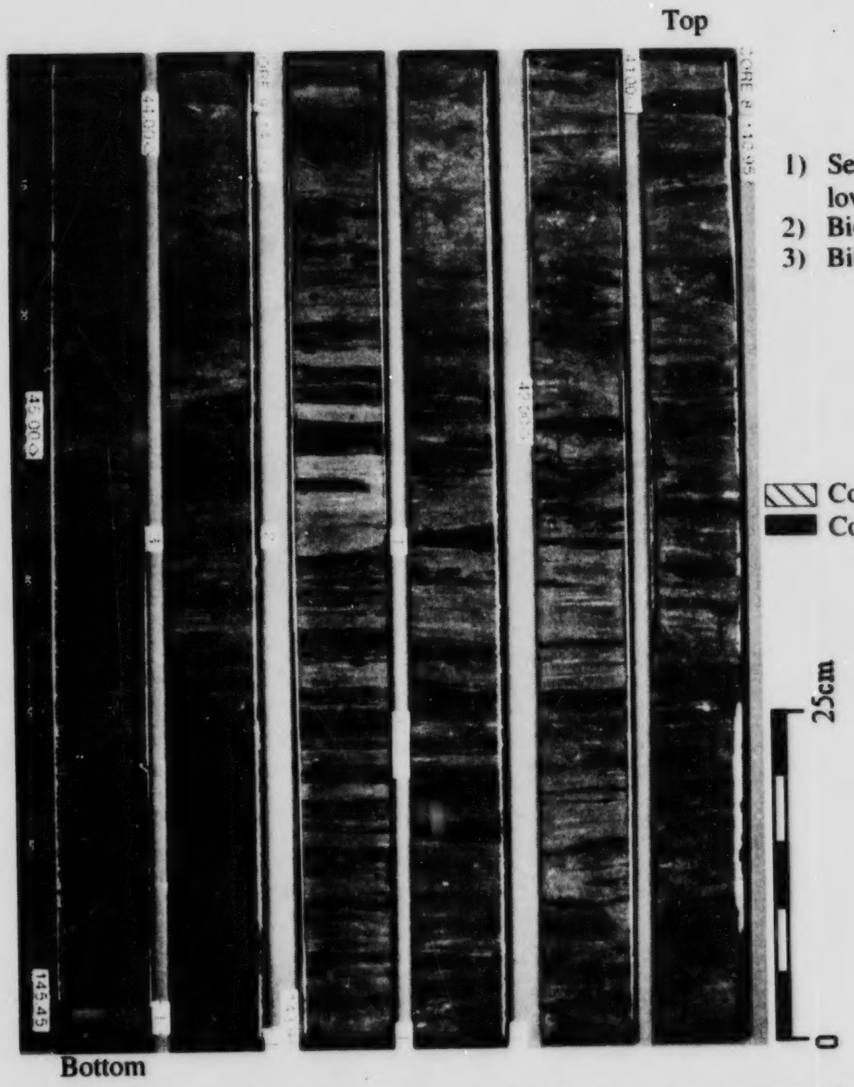
5.12D Facies 12D: Laminated to Thinly Interbedded, Bioturbated, Silty Mudstone

Facies 12D is a facies found within the Upper McMurray Formation. Interlaminated siltstone and mudstone characterizes the unit (Figure 65). Bioturbation structures are common, ranging from moderately to intensely burrowed. This facies averages 3.0 metre thick, ranging from about 0.5 metres thick to 5 metres. Rare, very fine-grained, carbonaceous material is dispersed within the silty interlaminae. This facies is a finer-grained equivalent to the laminated, muddy sand and sandy muds of Facies 12B and 12C.

Facies 12D is most common within the upper portion of the Upper McMurray. Facies 12D is commonly associated with the other subfacies of Facies 12 and 9.

Burrowed, interlaminated and thinly interbedded siltstone and mudstone facies has only been observed within the McMurray outcrops along the Ells River. In core Facies 12D is recognized by the prominent burrowing of siltstone and mud lithologies that occasionally destroys the original primary interbedded stratification.

Interpretation: This facies is interpreted as being deposited from suspension fall out from fluctuating tidal currents that flooded bays, secondary abandoned channels in a tidal flat or coastal plain setting. The two possibilities are within the mud-line of subtidal estuarine channels, with very high rates of suspended sediment fallout; or, within ponded, abandoned channels and bays in the tidal flat or coastal plain setting. Facies 12D is interpreted as a relatively common facies component of the transgressive estuarine deposit of the Upper McMurray succession. Paleogeographically Facies 12D is important because of the clear indication of somewhat fluctuating, but overall slow continuous deposition without obvious erosion.


Top
CORE 8 140.95
41.00
42.00
CORE 9
44.00
45.00
145.45
Bottom
25cm
0

1) Sedimentary Features: horizontal to low angle bedding, minor flasers
2) Bioturbation Index: 2-3
3) Bitumen Saturation: poor

▨ Cored Interval
■ Core Interval Viewed

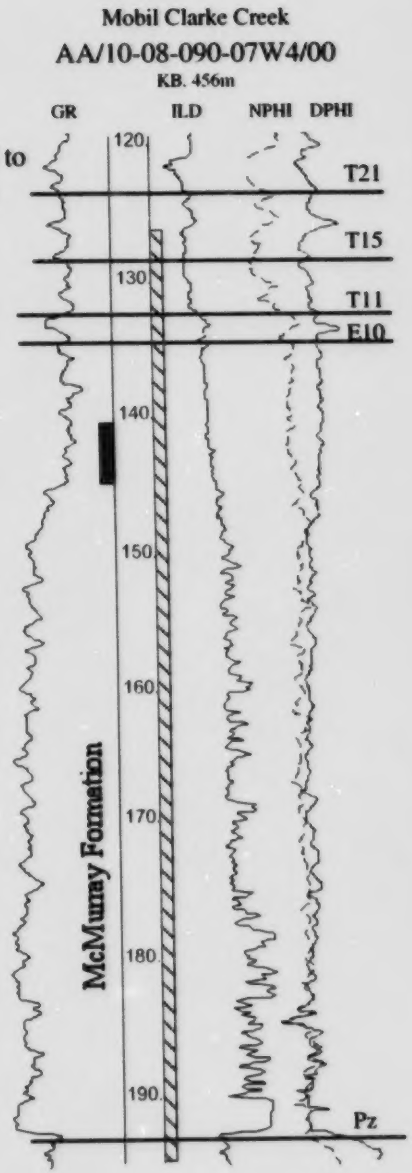


Figure 65: Variably bioturbated, laminated/thinly interbedded, silty mudstone and mudstone Upper McMurray Formation. Facies 12D. Geophysical log response shown to the right.

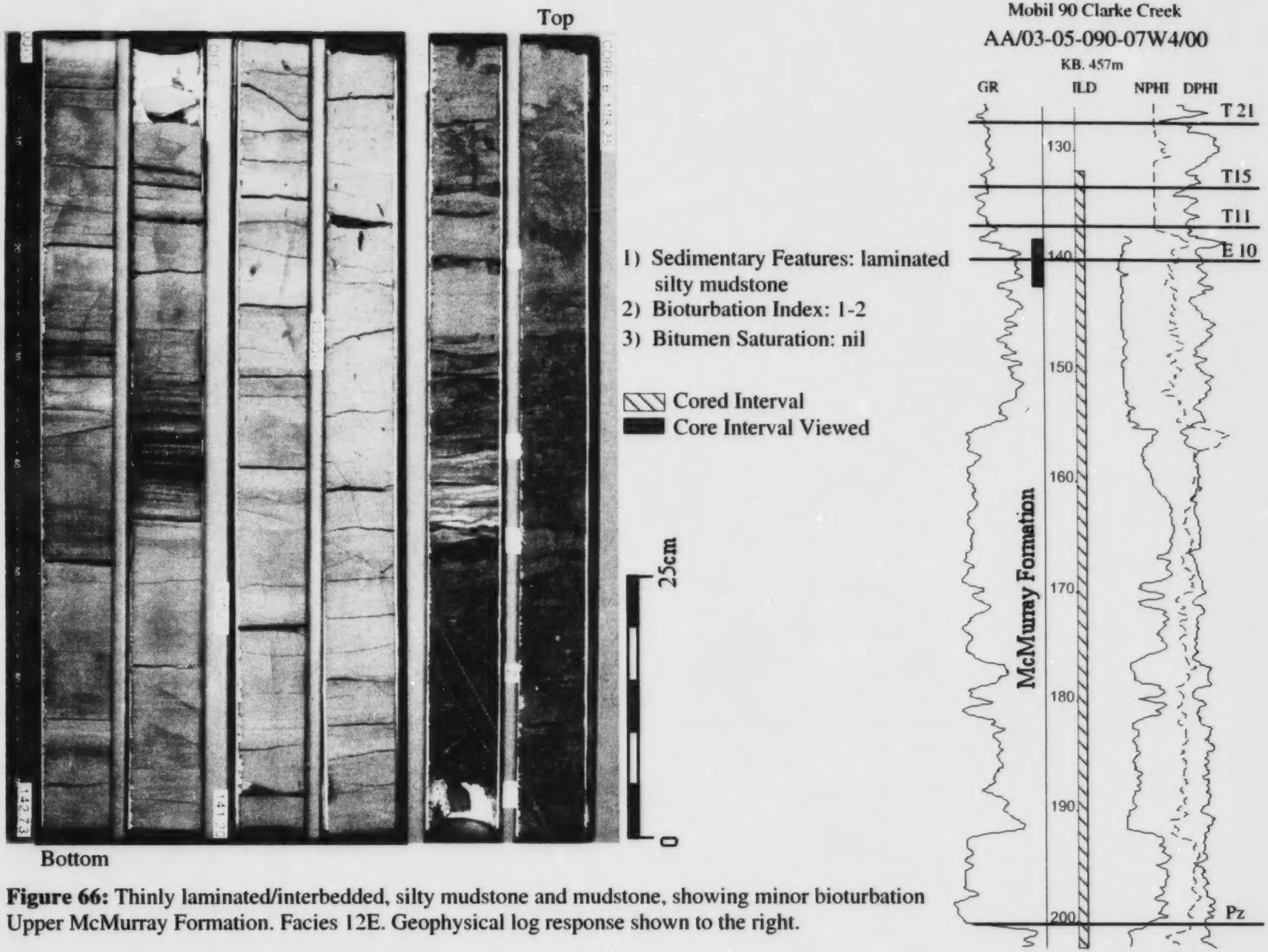
5.12E Facies 12E: Thinly Laminated Silty Mudstone/Mudstone

Facies 12E is a relatively common facies within the Upper McMurray succession. The mudstone facies is comprised of light to medium grey and tan grey, laminated, variably silty mudstone (Figures 66, 67). Bioturbation is rare with the exception of occasional the *Planolites* traces. The unit is usually faintly laminated and may contain significant siltstone. The siltstone is generally observed at the base of the facies interlaminated with mudstone (alternating tan brown and light grey banding) that gradually changes upward into light grey mudstone. The lower and upper contact with adjacent sand facies is usually sharp, while contacts with vertically adjacent muddy facies may be gradational, sharp or is sometimes burrowed. Facies 12E ranges in thickness < 0.2 metres to > 5 metres, but is usually < 2 metres thick. Minor carbonaceous debris may be present locally.

Facies 12E is found throughout the Upper McMurray succession, but is most prominent and thickest within the upper half of the interval. The mudstone facies is commonly associated with Facies 9A, 11, 12A, 12C, 12D, 15 and less commonly with Facies 5.

Facies 12E has rarely been observed in outcrop thus far. In core the facies is relatively common, being most prominent near the top of the McMurray Formation associated with other muddy facies of the Upper McMurray succession.

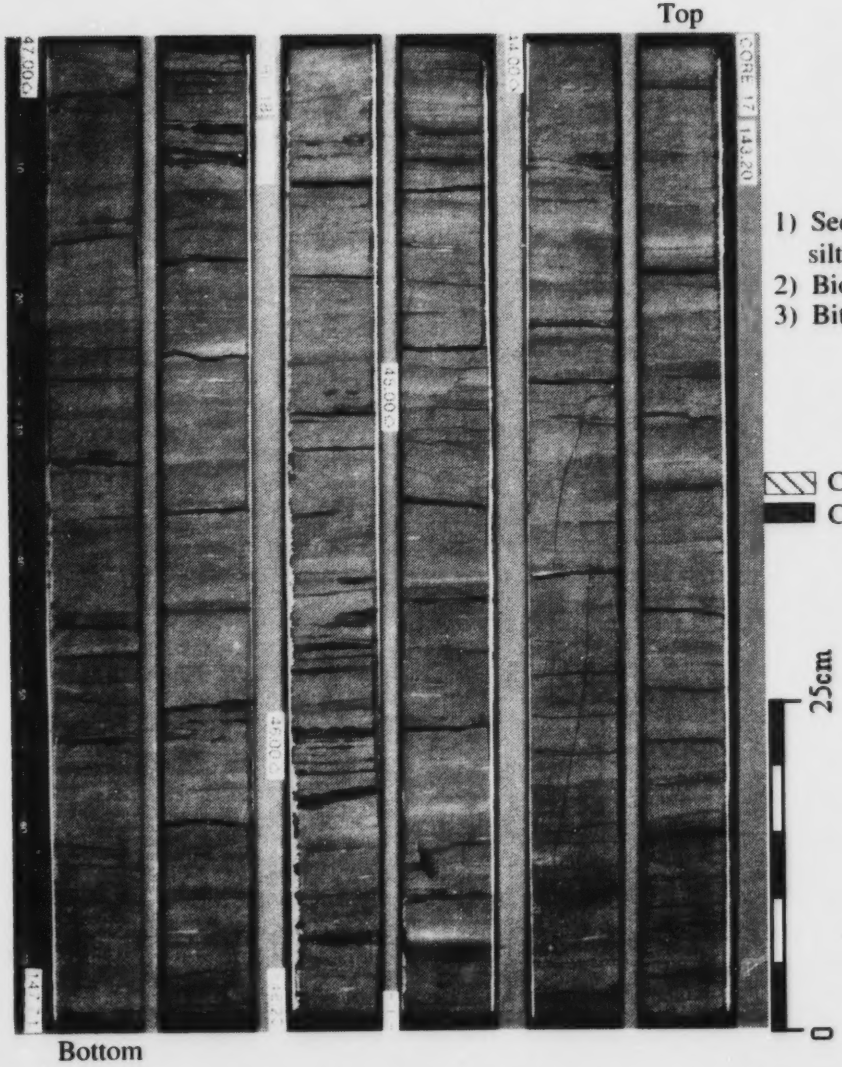
Interpretation: This facies is interpreted as being deposited from suspension fall out from fluctuating currents that flooded bays, secondary abandoned channels in a tidal flat or coastal plain setting. This facies is similar to Facies 12D in that it is interpreted as representative overbank/ flood plain deposits, as part of the vertical accretion deposits of abandonment phases of estuarine complexes. It is interpreted as a relatively common facies component of the transgressive estuarine deposit of the Upper McMurray succession. Paleogeographically Facies 12E is important because of the clear indication of somewhat fluctuating, but overall slow continuous deposition without obvious erosion.


Top
Bottom
25cm
0
142.73
141.70
Mobil 90 Clarke Creek
AA/03-05-090-07W4/00
KB. 457m
GR
ILD
NPHI
DPHI
T 21
T15
T11
E 10
Pz
130
140
150
160
170
180
190
200
McMurray Formation

1) Sedimentary Features: laminated silty mudstone
2) Bioturbation Index: 1-2
3) Bitumen Saturation: nil

▨ Cored Interval
■ Core Interval Viewed

Figure 66: Thinly laminated/interbedded, silty mudstone and mudstone, showing minor bioturbation Upper McMurray Formation. Facies 12E. Geophysical log response shown to the right.


Top
CORE 17
143.20
44.00
45.00
46.00
47.00
25cm
0
Bottom

1) Sedimentary Features: laminated silty mudstone
2) Bioturbation Index: 1-2
3) Bitumen Saturation: nil

▨ Cored Interval
■ Core Interval Viewed

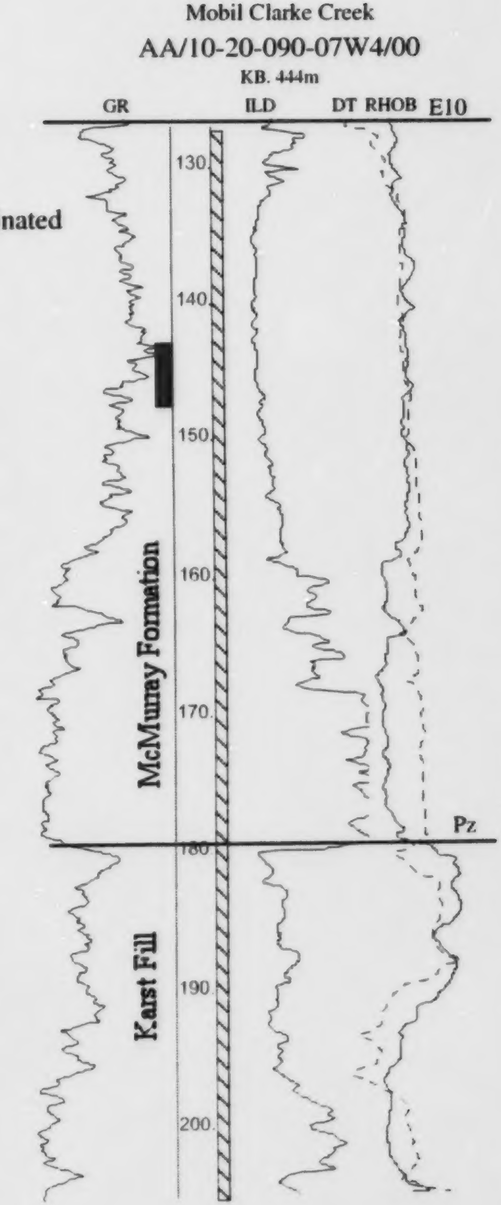


Figure 67: Thinly laminated/interbedded, silty mudstone and mudstone, showing minor bioturbation, Upper McMurray Formation. Facies 12E
Geophysical log response shown to the right.

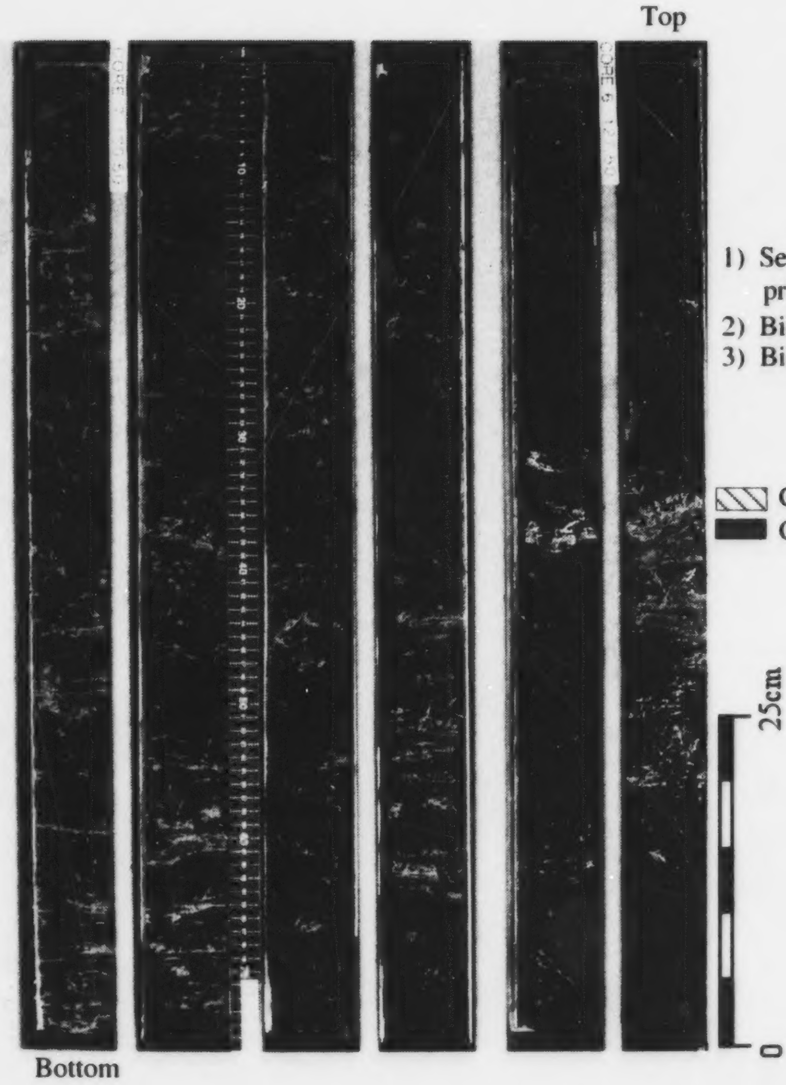
5.13A Facies 13A: Very Fine Grained, Heavily Burrowed, Muddy Sand

Facies 13A is one of the more common facies, generally confined to the upper portion of the Upper McMurray succession. Intensely to completely bioturbated, very fine grained, muddy sand characterizes this facies (Figure 68). Facies 13A averages about 1.5 metres thick, ranging from 0.2 m to greater than 8 m thick. This facies differs from some of the sandy facies of Facies 12 in that the sand and mudstone has been completely homogenized by burrowing (no or very little primary stratification preserved).

Facies 13A may alternate with the rippled sands of Facies 9A and B, cap Facies 10A and B, may grade up- or downsection into Facies 13B, 14 and the subfacies B through D of Facies 12. Facies 13A probably represents the totally burrowed equivalence of Facies 12B.

Thus far facies 13A has not been observed within outcrop exposures along the Athabasca River and associated tributaries. In core Facies 13A is recognized by complete churning and mixing of the mudstone and sand, with prominent trace fossils, namely *Planolites*, *Cylindrichnus*, with rare *Skolithos* and *Teichichnus*.

Interpretation: The environment where this facies is preserved has abundant bioturbation, indicative of slow, continuous sedimentation rates, without erosion and well oxygenated bottom water conditions. The two most likely possibilities are within the early abandonment phase (vertical accretion deposits) of subtidal estuarine channels that have a brackish water influence; or, protected brackish bays. Facies 13A is interpreted as one of the common facies of the transgressive estuarine deposits within the Upper McMurray succession.



1) Sedimentary Features: rare primary stratification preserved
2) Bioturbation Index: 4-5
3) Bitumen Saturation: fair

▨ Cored Interval
■ Core Interval Viewed

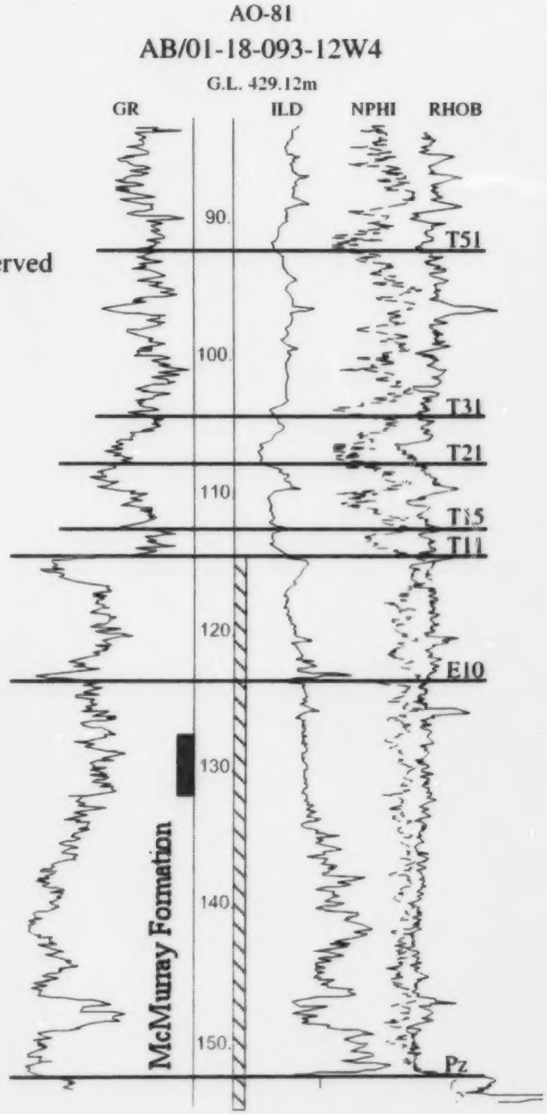


Figure 68: Burrow-mottled (churned) muddy sand with rare primary stratification and bedding preserved, Upper McMurray Formation. Facies 13A. Geophysical log response shown to the right.

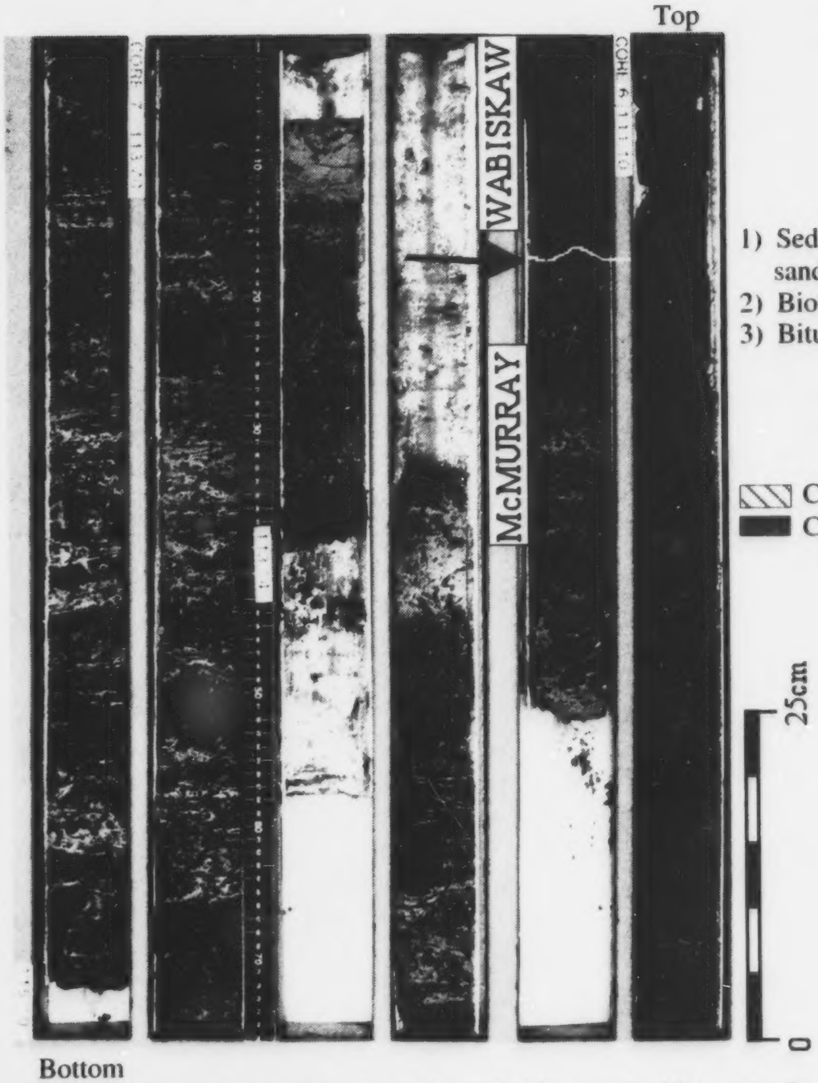
5.13B Facies 13B: Intensely Burrowed Silty Mudstone/Muddy Silt

Intensely bioturbated silty mudstones and muddy silt of Facies 13B are confined to the Upper McMurray succession. Facies 13B is the mudstone-dominated equivalent of Facies 13A (Figure 69). The bioturbated silty mudstone aned muddy silt units average about 1.0 m thick, ranging from 0.2 metre to greater than 5 metres thick. Rare, very thin, discontinuous coal interlaminae and fragments are present locally. The main distinction between Facies 13A and 13B is the shift from sandy (13A) to silty mudstone/muddy silt (13B).

As with its sandy equivalent (Facies 13A), Facies 13B may alternate with the rippled sands of Facies 9, cap Facies 10A and B, may grade up- or downsection into Facies 13B, 14 and the subfacies of Facies 12. Facies 13B probably represents the totally burrowed equivalence of Facies 12C.

Thus far facies 13B have not been observed in exposures viewed along the Athabasca River and associated tributaries. In core Facies 13B is recognized by complete churning and mixing of the sandy mudstone, with prominent trace fossils, namely *Planolites*, *Cylindrichnus* and *Teichichnus*.

Interpretation: This facies is interpreted as being deposited from suspension fallout within sediments of the Upper McMurray Formation. The environment where this facies is preserved has abundant bioturbation features, indicative of slow, continuous muddy sedimentation rates with little erosion and well-oxygenated bottom water conditions. The most likely possibilities are within the later stage, muddy abandonment phase of estuarine channels that had a brackish influence; or, protected brackish bay environments. This facies is part of the vertical accretion abandoned channel fill deposits of the Upper McMurray Formation. Facies 13B is interpreted as one of the common facies of the transgressive estuarine deposits.



1) Sedimentary Features: churned sandy mud
2) Bioturbation Index: 5
3) Bitumen Saturation: fair

▨ Cored Interval
■ Core Interval Viewed

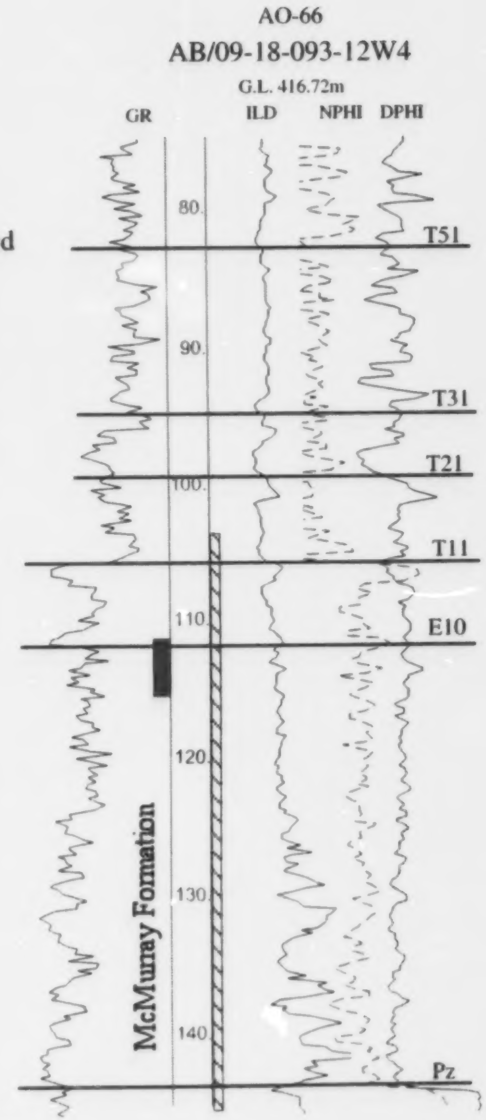


Figure 69: Burrow-mottled (churned) sandy/silty mud with some primarly stratified and flaser-bedding preserved, Upper McMurray Formation, unconformably overlain by burrowed, wavy-bedded Wabiskaw Member sediments (arrow). Facies 13B.
Geophysical log response shown to the right.

5.14 Facies 14: Coaly and/or Rooted, Sandy-Muddy Siltstone to Silty Mudstone

Facies 14 is a thin unit within the Upper McMurray succession. Rooted, often rippled muddy siltstone to silty mudstones characterizes the facies (Figures 70 to 72). Other forms of bioturbation are rare. This facies averages 0.30 metres thick, ranging from about 0.1 to 0 .75 metre thick. Silty mudstones may be mottled, nodular or concretionary, with local sideritic, and ferruginous cement. The siltstone dominated horizons have a yellowish-brown colour; are well sorted, typically rippled and contain well defined, blackened, vertical to sub-vertical root traces. Very thin carbonaceous laminations are common.

Facies 14 is usually found near the top of the Upper McMurray succession often associated with facies 3, 8B, 9A, 12B, 12C, 12D, 13A, 13 B and 15. The thin Facies 14 unit is generally poorly preserved due to subsequent erosion.

Rooted horizons have been reported from a number of outcrops along the Athabasca, Steepbank, MacKay and Ells rivers, most of which being found near the top of the McMurray succession. In core, Facies 14 is recognized by root traces (some of which show downwards branching patterns), by vertical to sub-vertical tubes, containing the carbonized and/or coalified remains of the original roots. Some of the original organic material has been altered through siderization or pyritization.

Interpretation: This facies is interpreted to represent paleosols that developed in vegetated areas of floodplains, tidal flats or coastal plain setting. Facies 14 is interpreted as a relatively common facies found within the transgressive estuarine deposits of the Upper McMurray Formation. The occurrence of Facies 14 is paleogeographically important because of the clear indication this facies gives of deposition under conditions of relatively lower sedimentation rates, in subaerial and vegetated settings.

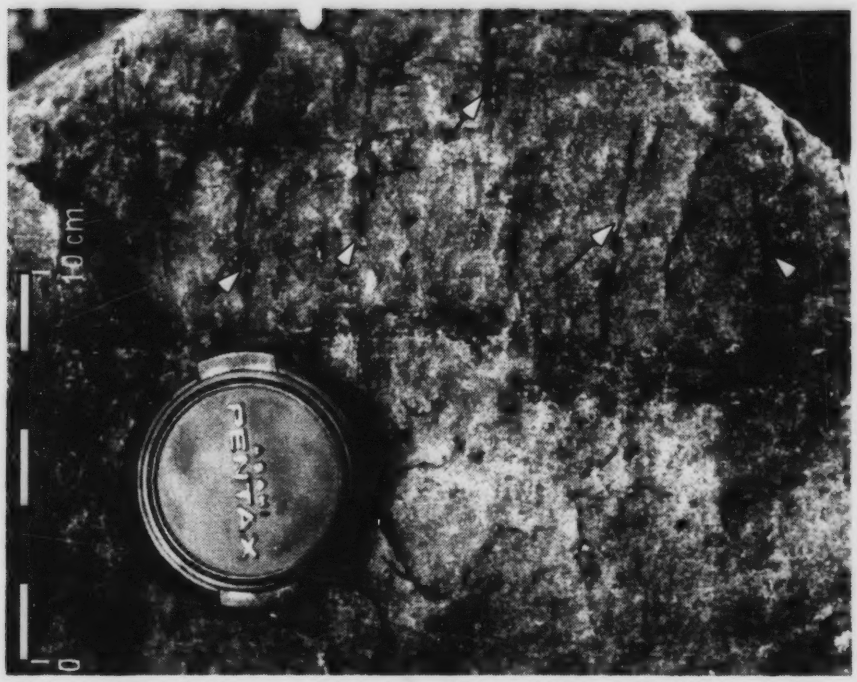


Figure 70: Rooted (arrows) siltstone,Upper McMurray Formation, Outcrop #9-2, Steepbank River. Facies 14.

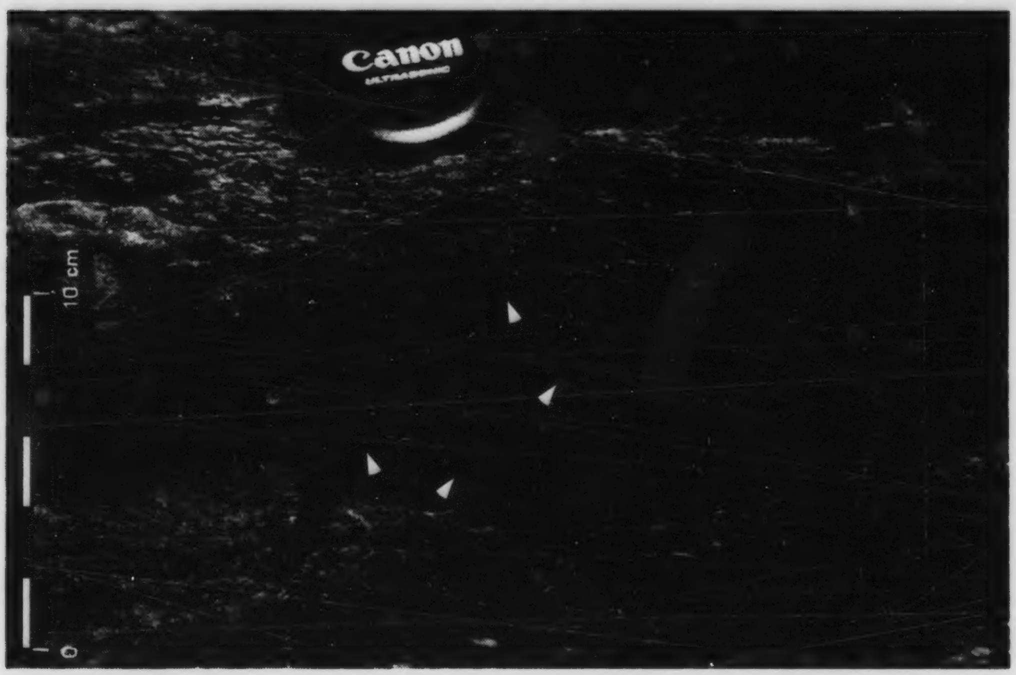
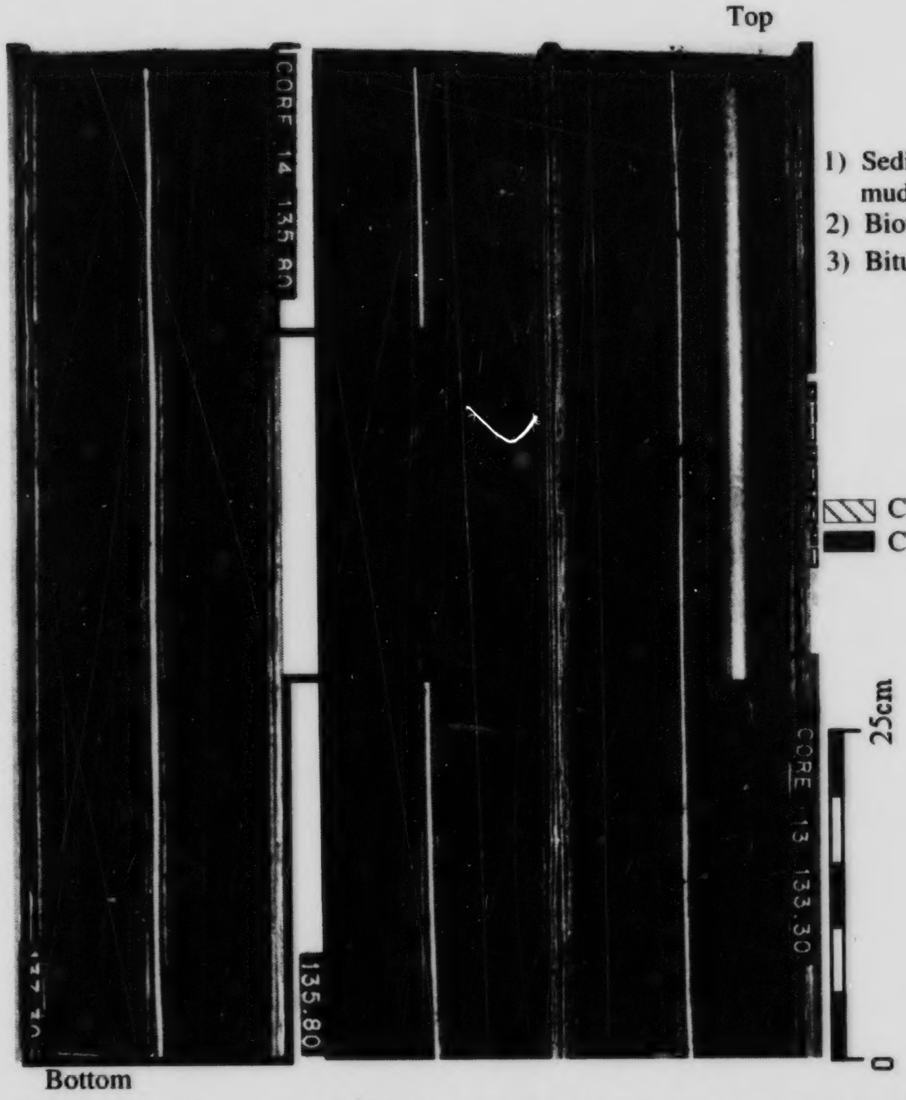


Figure 71: Rooted (arrows) muddy sand, capped by burrowed sandy siltstone, Upper McMurray Formation, 25-metre level in section #2, Outcrop #9, Steepbank River. Facies 14.


Top
CORE 14 135.80
135.80
CORE 13 133.30
25cm
0
Bottom

1) Sedimentary Features: bifurcating mud lams
2) Bioturbation Index: 2-3
3) Bitumen Saturation: poor-fair

▨ Cored Interval
■ Core Interval Viewed

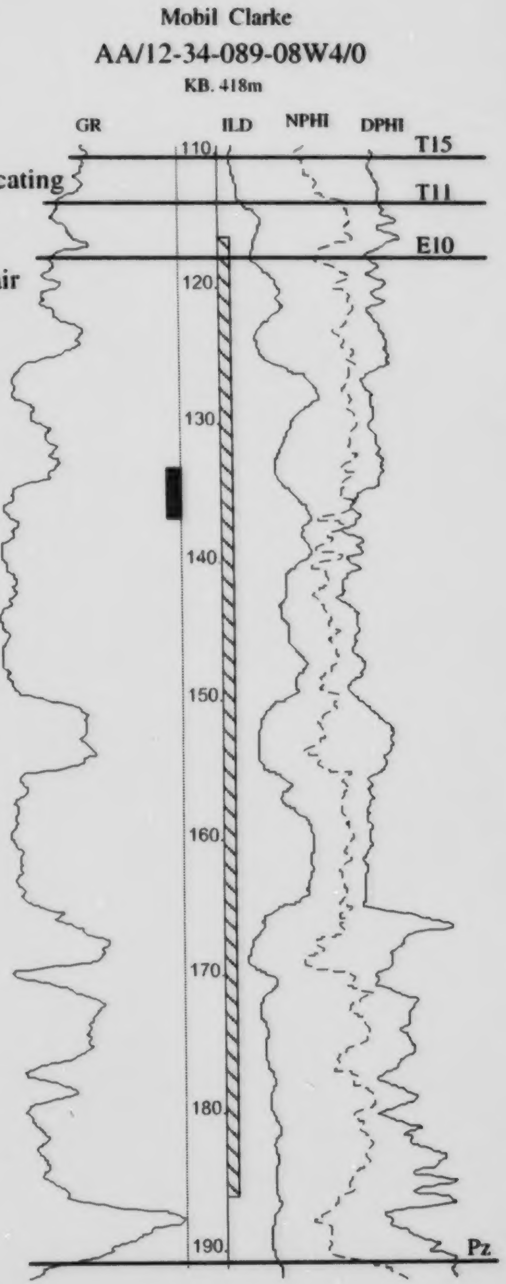


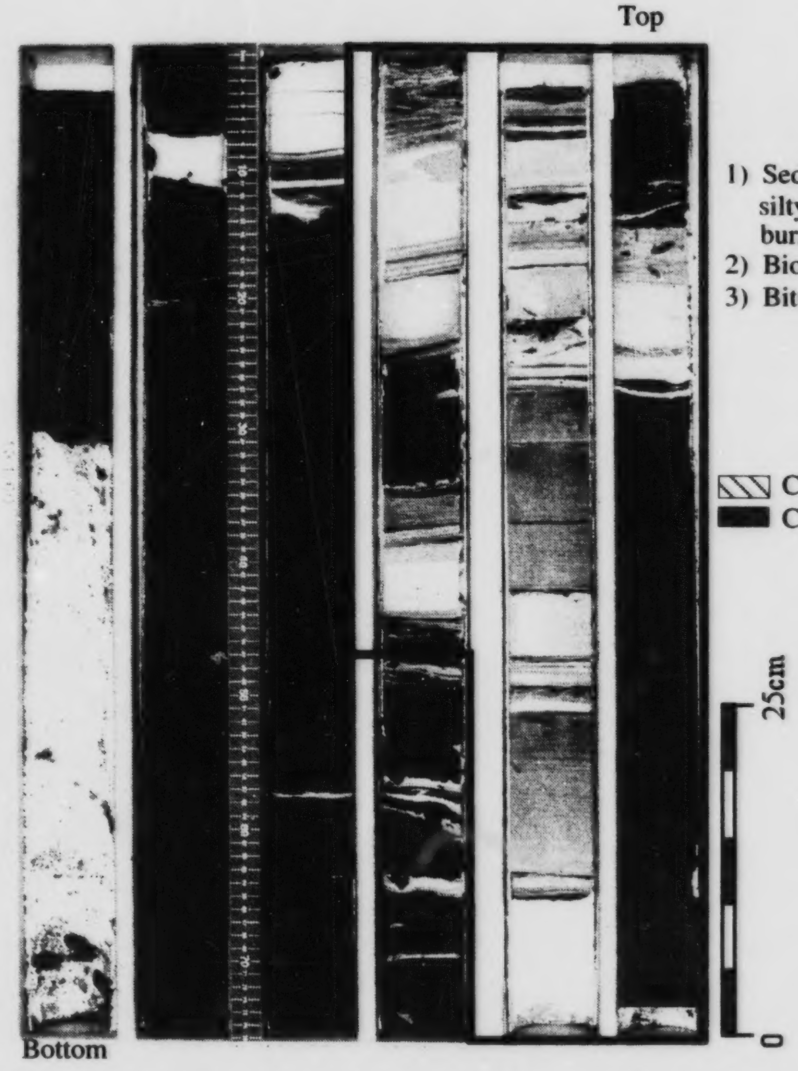
Figure 72: Carbonaceous muddy sand, alternating with coaly interlaminae, Upper McMurray Formation. Facies 14. Geophysical log response shown to the right.

5.15 Facies 15: Coarsening-Upward Mudstone-Siltstone-Sand

Facies 15 is rare, found predominantly in the Upper McMurray Formation. Very fine to fine grained, variably stratified and/or crossbedded, quartz-dominated sand, that gradually coarsens upward from mudstone to silty-mudstone to sandy siltstone to silty sand, characterizes the unit (Figure 73). Coarsening-upwards packages of this facies average 1.0 metres thick, ranging from 0.5 to 3.0 metres thick. The sand component is rounded to well-rounded, and moderately to very well-sorted. Carbonaceous material is dispersed as comminuted debris, or as lag concentrations of coalified and mummified twigs. Internally the stratification and cross bedding structures change upsection, concomitant with the increase in grain size. At the base are horizontally stratified mudstones and siltstones that change upsection into wispy laminated and rippled sandy silty mudstone and sandy siltstone. As the grain size increases, sands show a variety of cross bedding associated with horizontal stratification, including current and wave ripples, small scale, planar tabular cross bedding and convolute lamination.

The upward coarsening units of Facies 15 are most often situated within the middle to upper portions of the Upper McMurray succession. Facies 15 is commonly associated with Facies 11, 12B, 12C, 12D, 13A, 13B and 16. A gamma ray profile frequently displays a funnel shape curve associated with the upward coarsening from mudstone to sand (Figure 73). Thin, stacked, coarsening upward cycles have been observed locally near the top of the Upper McMurray Formation. These thin cycles usually cap sandy/silty mudstone. Most of the documentation of the upward coarsening successions of Facies 15 has been done in core. In core, the upward coarsening successions appear to be deposited in mainly horizontal packages, that are laterally discontinuous in the subsurface, and cannot be traced from core to core.

Interpretation: The most likely origin for this facies are crevasse splays that build into bays or shallow lakes, or along the edges of estuarine channels. These deposits likely reflect overbank flooding of the meandering channels where channel margins were breached depositing flood sediments onto the interfluvial regions comprised of mud, sand and mixed tidal flat sediment. Facies 15 is interpreted as one of the common facies preserved in the transgressive estuarine deposits of the Upper McMurray.



1) Sedimentary Features: laminated silty mudstone, few wavy burrowed muds
2) Bioturbation Index: 2
3) Bitumen Saturation: good

▨ Cored Interval
■ Core Interval Viewed

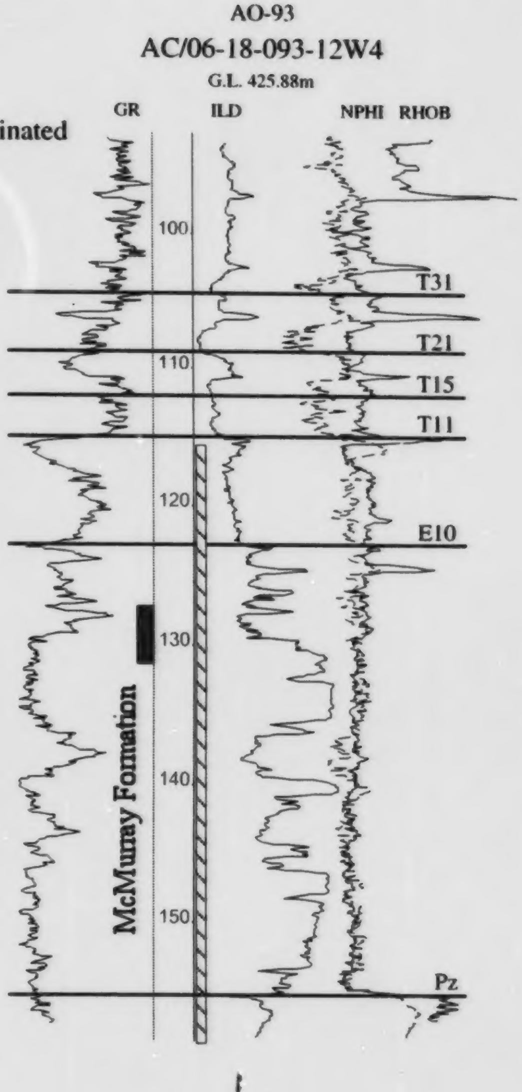


Figure 73: Coarsening-upward units of mud-silt-sand. Facies 15. Geophysical log response shown to the right.

5.16 Facies 16: Very Fine to Fine Grained, Well Sorted, Wave-Rippled Sand

Facies 16 is generally confined to the uppermost portion of the Upper McMurray succession. Very fine to fine grained, wave rippled, quartz-dominated sand characterizes the unit (Figure 74, 75). Beds average 0.25 metres thick, ranging from thin wispy interlaminations < 0.01 metres to 0.75 metres thick. The sand is rounded to well rounded, and well sorted. The overall appearance of bedding within Facies 16 is wavy and parallel. Thin, discontinuous mudstone laminations occur within the facies.

The wave-rippled sand is associated with the very fine to fine-grained sandy and muddy sand facies common at the top of the McMurray Formation. These facies include current rippled and flaser bedded sand (Facies 9A, 9B); horizontally stratified sand (Facies 11); interbedded muddy sand units of (Facies 12A, 12B); burrow mottled argillaceous sand (Facies 13A); rooted sandy and muddy siltstones (Facies 14), and coarsening upward mudstone-siltstone-sand successions (Facies 15).

The wave-rippled sand has only been noted in a few isolated outcrops, including those along the Horse, Steepbank, MacKay and Ells rivers. In all cases the facies was encountered near the top of the exposures within the Upper McMurray Formation. In several outcrop exposures the top of prominent, undulatory, wave rippled surfaces display very small (30 cm wide by 20 cm deep) scours having a swaley to small scale cross bedded sand fill. In core prominent and well-defined wave-ripples and apparent bimodal paleoflows characterize Facies 16. Less commonly wave rippled sands are convoluted, with small ball-and-pillows or oversteepened cross bedding, indicative of very rapid sedimentation from waves, and early syndepositional dewatering.

Interpretation: This facies is interpreted as being deposited from bi-directional oscillatory waves that formed in near coastal settings and locally in smaller lakes and bays. The wave-rippled sands are locally associated with tidal flat sediments, or with brackish bay or vertical abandoned channel successions that were effectively small lakes. In all cases this facies is indicative of oscillatory, high- to medium-energy currents that occurred in openwater areas that were sufficient to generate waves. The small scale scour and fill may indicate a low gradient drainage network across which tides receded, creating sheets of wave-rippled sand and runnel-networks. Facies 16 is interpreted as one of the less common facies preserved in the transgressive estuarine deposits of the Upper McMurray succession.

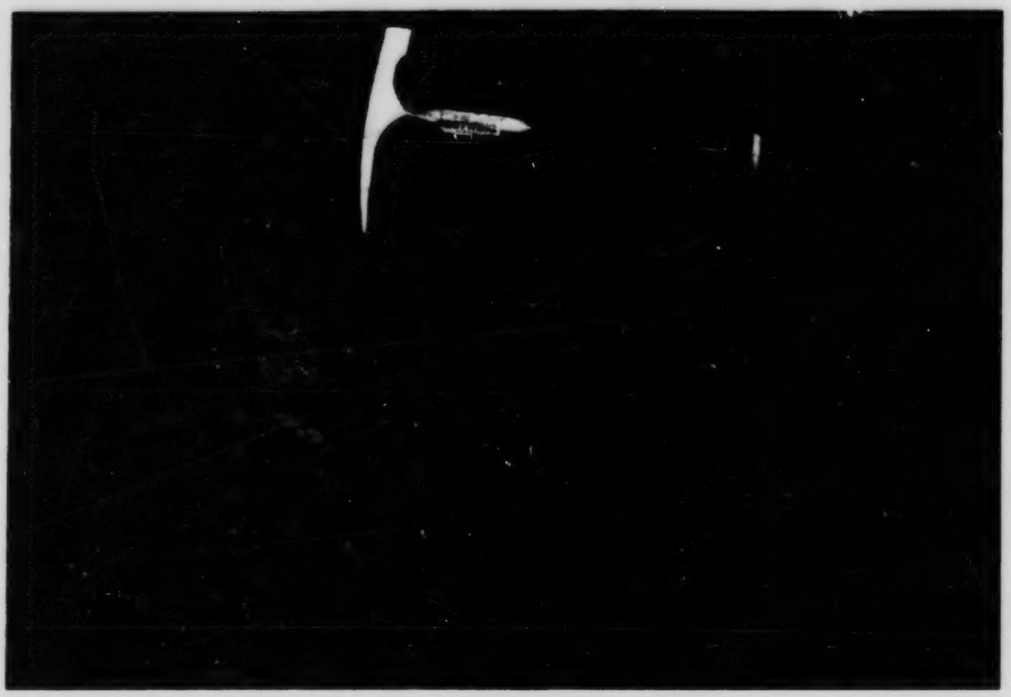


Figure 74: Wave-rippled, very fine to fine grained sand, bedding plane top view showing sinuous, out-of-phase wave-ripples, Upper McMurray, Ells River. Facies 16.

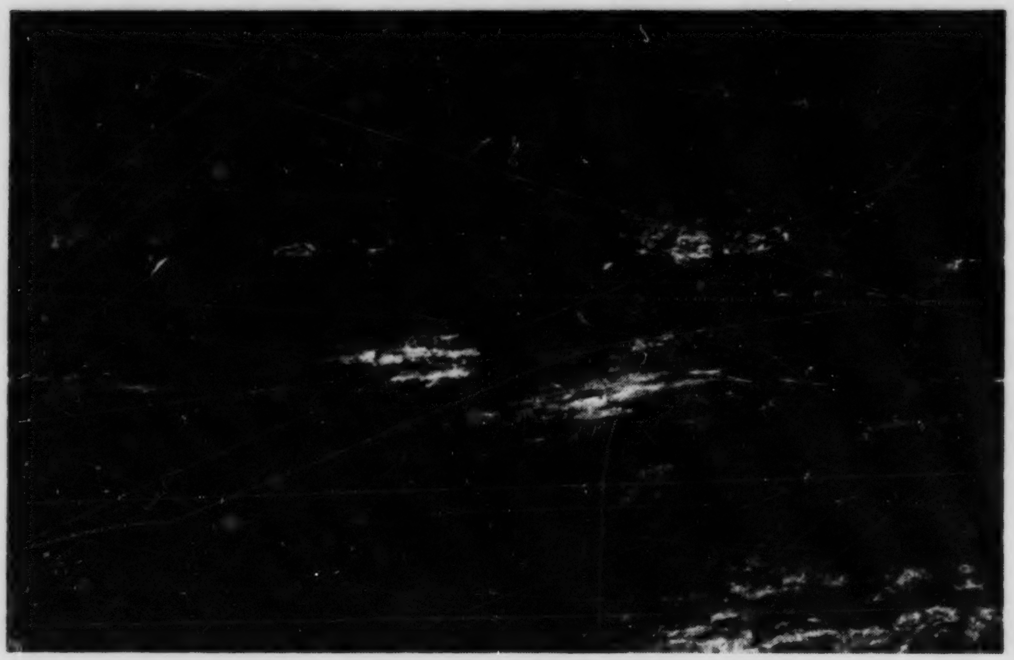


Figure 75: Wave-rippled, very fine to fine grained sand, showing sinuous, out-of-phase wave-ripples in cross section, Upper McMurray, Ells River. Facies 16.

5.17 Facies 17: Silicified Sandstone ('Beaver River Sandstone')

Facies 17 is a very rare facies associated with the Lower McMurray fluvial succession (Figures 76, 77). This facies averages < 1 m thick, ranging from a few decimetres to about a metre in thickness. In some units, diffuse pedogenic mottling occurs. The facies is a white, silica-cemented sandstone that is highly indurated. In outcrop the unit is resistant. The silica-cemented sandstones mainly occur in the Fort MacKay area, and at the Beaver River Sandstone quarry occur as small, low and isolated outcrops. On bedding plane surfaces and in cross section are root trace imprints, some of which are up to 1 cm in diameter. Abundant comminuted organic detritus occurs throughout the sandstone, and within loose rubble, including fossils stems, branches and coaly debris. Limited palynological dating done on a coaly fragment from this sandstone yielded a modest terrestrial assemblage of palynomorphs that appear to be Aptian-Cenomanian in age. Sedimentary structures are poorly developed, with only the root traces observed. This facies is found on the MacKay River outcrops, at the quarry site along Beaver River, and in subsurface core in the Fort MacKay area.

Interpretation: The silica cement makes this sandstone distinct lithologically from the other more typically uncemented McMurray sands. The interpretation is that the silica-cemented sandstone of this facies was within karstic paleolows at the time of cementation. Cementation may have been associated with silica-saturated connate waters. Quite commonly sideritization and siderite cement is associated with the silica-cemented sands. Diagenesis of the Beaver River Sandstone was examined by Brian Tsang as part of his M.Sc. thesis work ant the Department of Geology and Geophysics, The University of Calgary (Tsang, 1998).

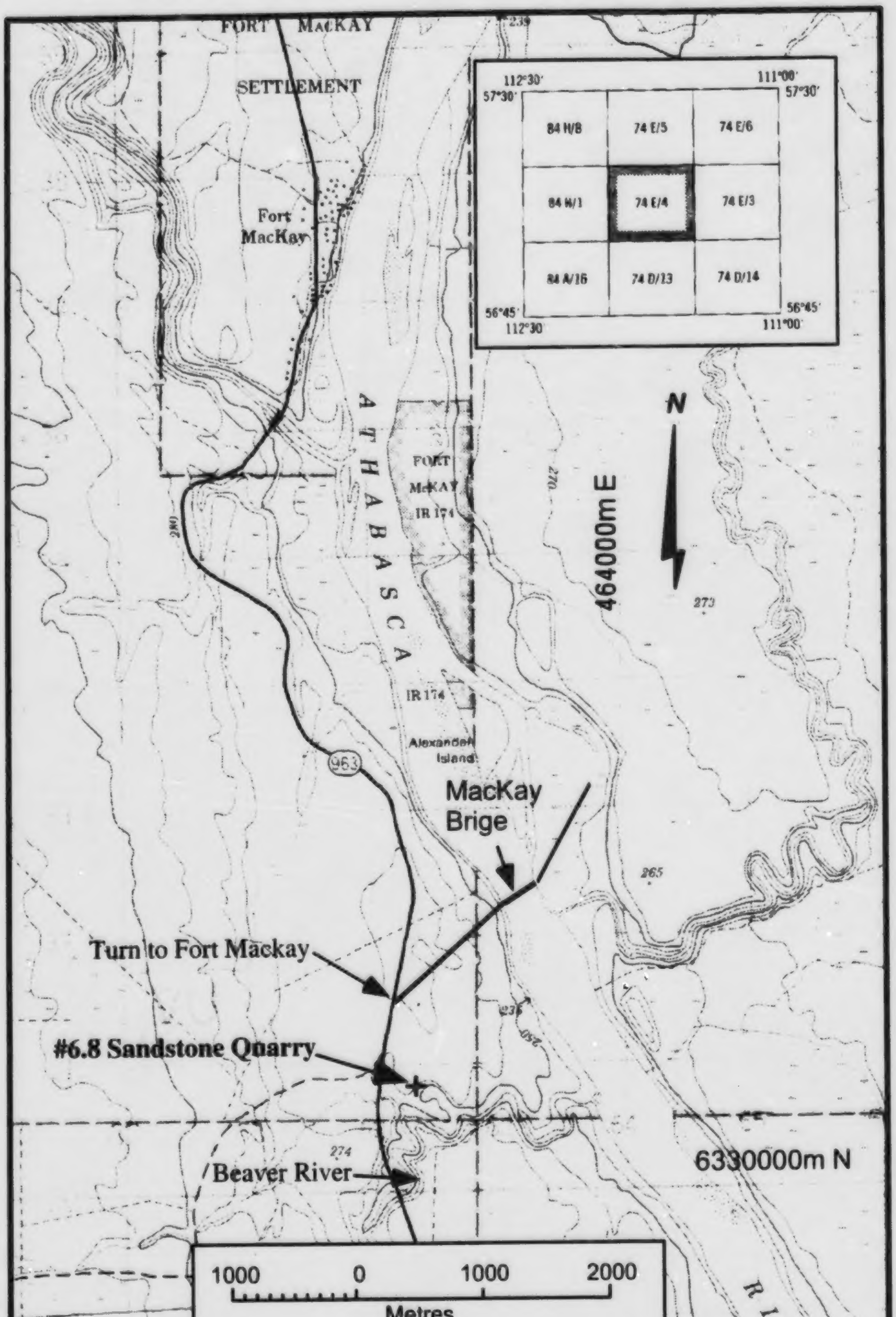
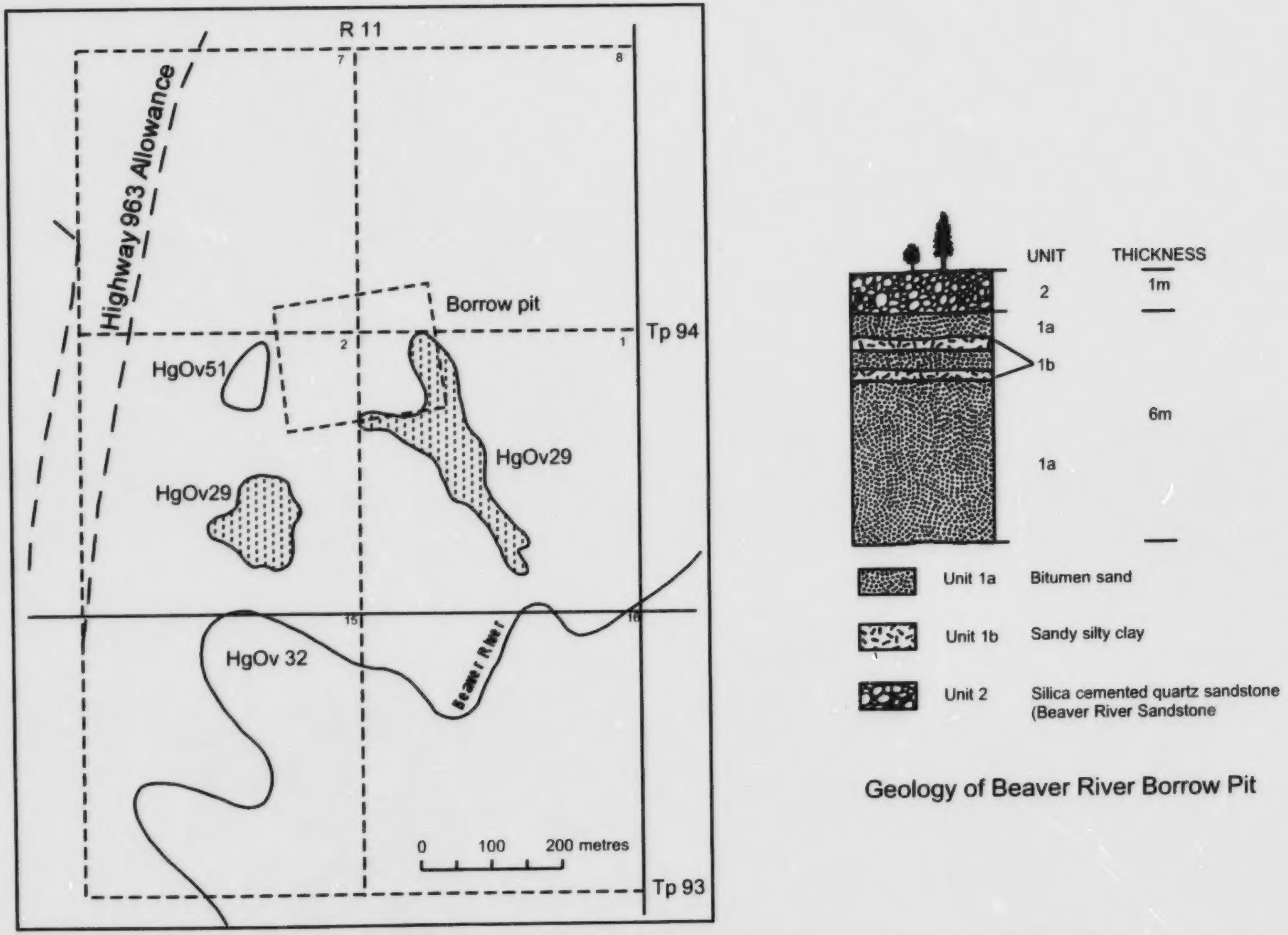

FORT MACKAY
SETTLEMENT
Fort MacKay
ATHABASCA
FORT McKAY IR 174
IR 174
Alexander Island
963
MacKay Brige
Turn to Fort Mackay
#6.8 Sandstone Quarry
Beaver River
464000m E
6330000m N
N
1000
0
1000
2000
Metres
RIV
112°30'
57°30'
111°00'
84 H/8
74 E/5
74 E/6
84 H/1
74 E/4
74 E/3
84 A/16
74 D/13
74 D/14
56°45'
273
265
274

Figure 76a: Map showing location of Beaver River sandstone quarry, Fort MacKay


R 11
7
8
Highway 963 Allowance
Borrow pit
Tp 94
2
1
HgOv51
HgOv29
HgOv29
15
16
HgOv 32
Beaver River
0
100
200 metres
Tp 93
UNIT
THICKNESS
2
1m
1a
1b
6m
1a
Unit 1a
Bitumen sand
Unit 1b
Sandy silty clay
Unit 2
Silica cemented quartz sandstone
(Beaver River Sandstone

Geology of Beaver River Borrow Pit

Figure 76b: Detailed location map and stratigraphic section of Beaver River sandstone quarry, Fort Mackay

5.18 Facies 18: Poorly Sorted, Karstic Calci-/Siliciclastics

Facies 19 is a rare facies found only along the basal unconformity of the McMurray Formation. Deeply weathered karstic limestone breccia, infilled with variable amounts of clastic detritus, characterize this facies (Figures 79, 80). This facies averages 2.0 metres thick, ranging from about 0.5 to > 5 metres thick. Karstic infill exists in a variety of forms ranging minor, low relief, subtle collapse features to complex, karst-induced features, including sinkhole development, caving and brecciation. It is often difficult to recognize karstic infill within the subtle, low relief collapse regions because the features are simply filled with sediments of the McMurray Formation (Lower or Upper). Sediment ranges from fine to coarse-grained, cross-bedded to massive, sand to mudstone-filled depressions, often containing carbonaceous debris. Slump structures and synsedimentary faults are common. At the other end of the spectrum the complex, extreme karst regions are easy to identify. Several boreholes in the Athabasca oil sands area have penetrated sinkholes and other collapse features. In core, karstic infill features include: carbonate brecciation; slumped sediment blocks; highly distorted bedding; steeply-inclined to vertical bedding; and, the apparent interbedding of Cretaceous McMurray siliciclastics and Devonian carbonates of the Waterways Formation.

Post-depositional mineralization within some of the karstified successions is sometimes more pronounced than elsewhere in the Athabasca region. In some karstic units, diffuse pedogenic mottling occurs that is typically nodular or concretionary, with local pyritic, sideritic, ferruginous, and rarely silicic cement. The karst sediment is variably saturated with bitumen. Pyrite is common both as nodules and cement; siderite cement and replacement is also common. Rare chalcopyrite, sphalerite and manganese mineralization occurs in the karst fill.

Karst regions in the Athabasca area are reasonably well known and somewhat predictable. Regional geological knowledge can help identify these subtle karst related successions. The deeply weathered, karstic and sideritized carbonate bedrock is recognized in some regions where Devonian carbonate is exposed along the rivers and their tributaries in the Fort McMurray area. Extreme relief along the pre-Cretaceous unconformity is particularly apparent along the MacKay and Muskeg rivers where a pronounced, small scale, dome-and-basin style of topography is dominant. The same, but more subtlely displayed structural style also exists along the adjoining Athabasca River. It is important to note along the Athabasca River, north of Fort McMurray (downstream), the dome-and-basin topography is appreciable, whereas west of Fort McMurray (upstream) the Devonian exposures gradually flatten to a more uniform, monoclinal pattern.

In core, Facies 19 is recognized by the occurrence of dissolution cavities / vugs and the highly distorted, slumped and apparent interbedded calci-and siliciclastic sediment. This unit grades downsection into unaltered and fresh Devonian limestone.

Interpretation: This facies is interpreted as being a deeply weathered karst limestone that developed within the Devonian limestone succession prior to and during emplacement of the Cretaceous McMurray Formation. Later deposition of Lower and Upper McMurray siliciclastic units infilled the karstic depressions, locally resulting in admixing of calciclastic and siliciclastic lithologies.

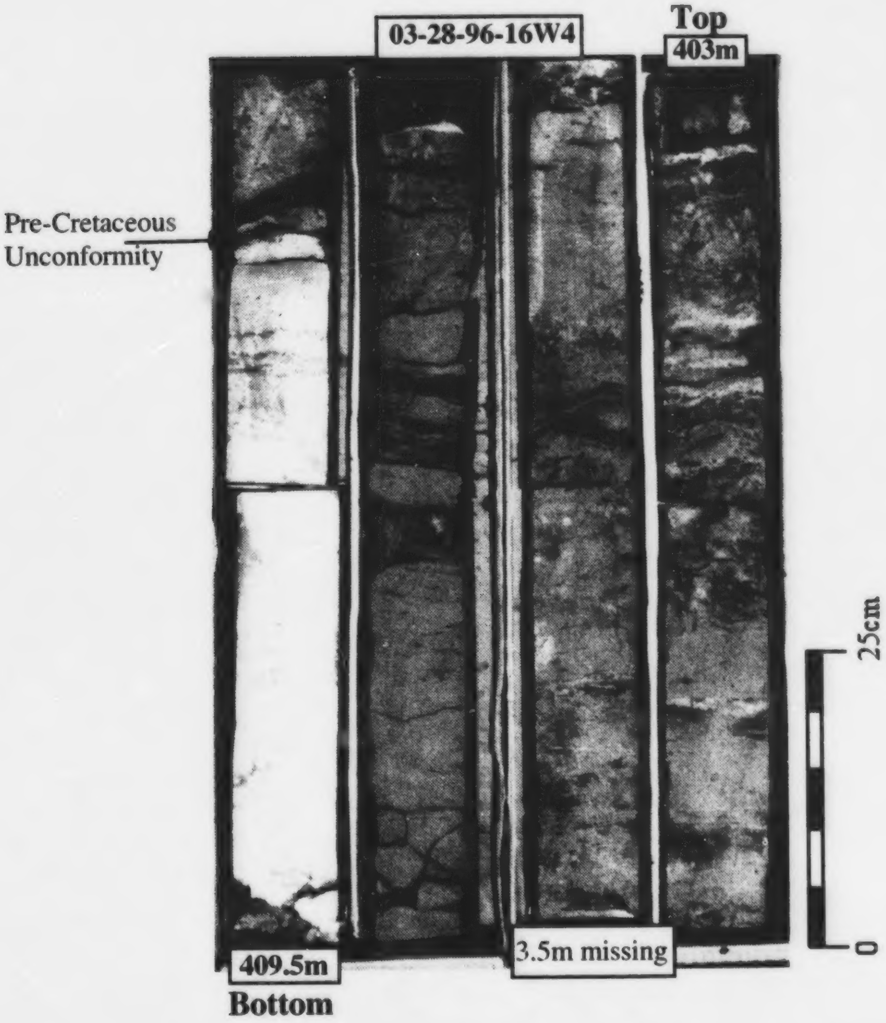
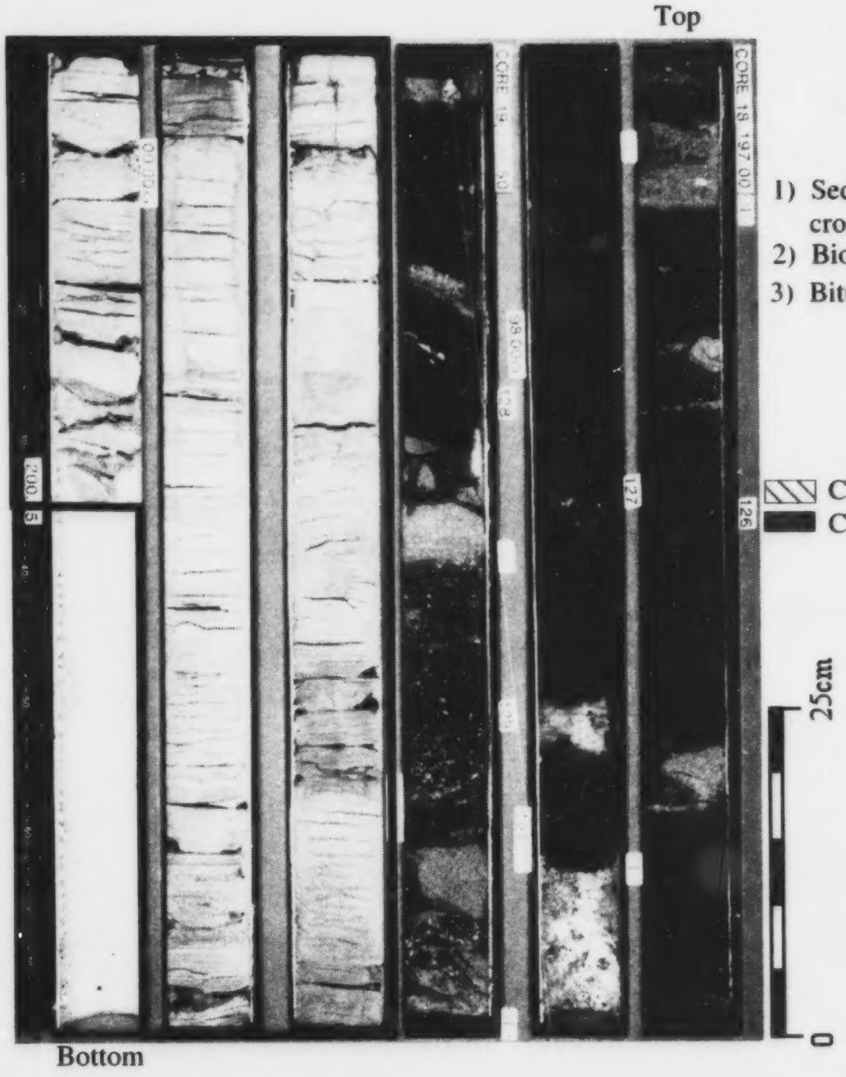

03-28-96-16W4
Top
403m
Pre-Cretaceous Unconformity
25cm
0
3.5m missing
409.5m
Bottom

Figure 77: Weathered, nodular carbonate at the pre-Cretaceous unconformity, indicated by the arrow, overlain by carbonaceous to coaly silty mudstone (Facies 3) and rooted, very fine to fine silty/sandy mudstone (Facies 4), Devonian Waterways Formation overlain by Lower McMurray Formation.


Top
CORE 18 197.00
126
127
CORE 19
98.00
128
200.
5
Bottom
25cm
0

1) Sedimentary Features: trough cross beds, laminated mud
2) Bioturbation Index: 1
3) Bitumen Saturation: fair

▨ Cored Interval
■ Core Interval Viewed

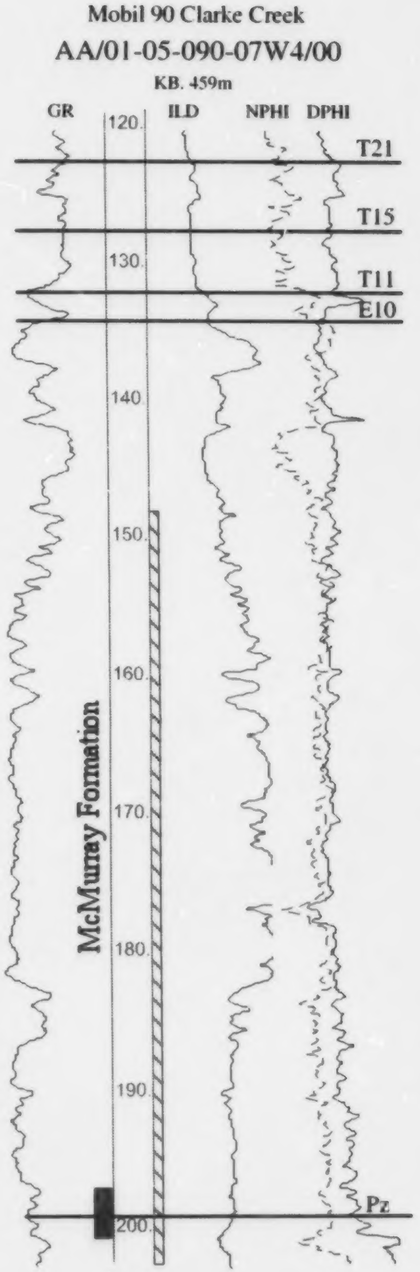
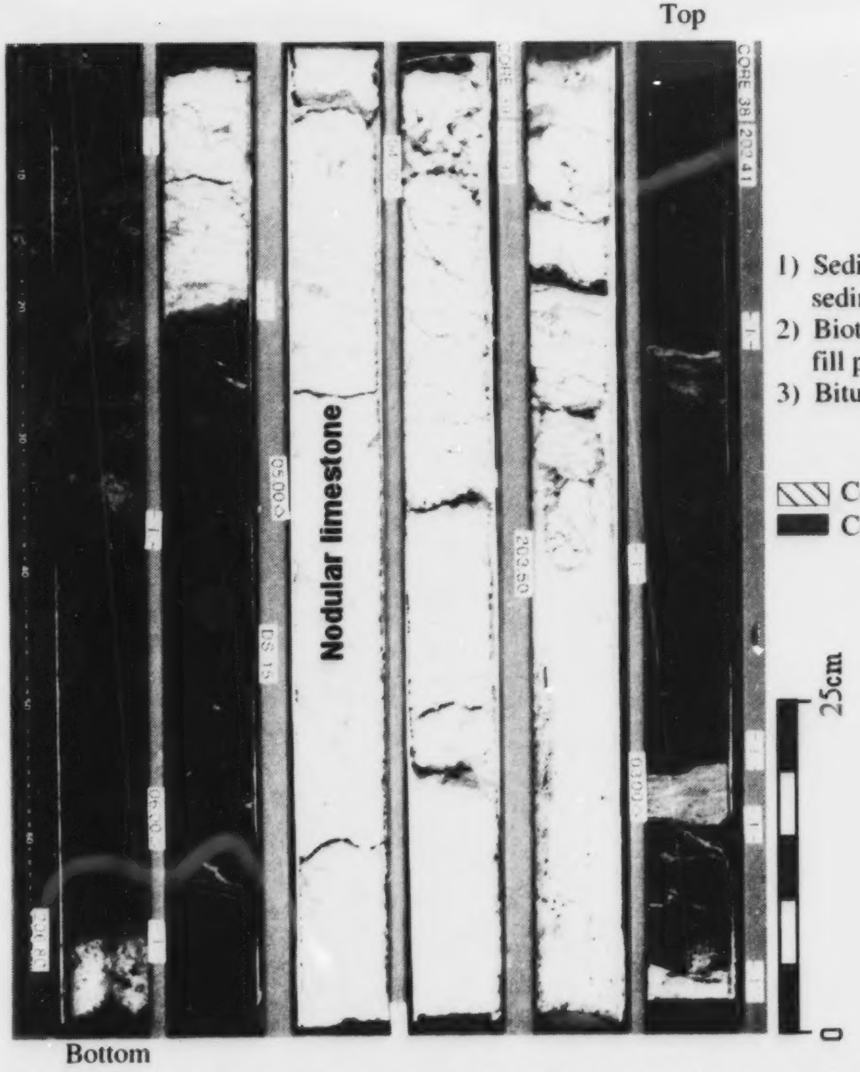


Figure 78: Thin, laminated carbonate overlain by Karst-infill of slumped and trough cross-bedded, pebbly sand and gravel (Facies 1, 2, 7B), Devonian Waterways Formation overlain by Lower McMurray Formation. Geophysical log response shown to the right

Top



Bottom

1) Sedimentary Features: slumped sediment
2) Bioturbation Index: 2 sandy karst fill pre-collapse
3) Bitumen Saturation: good

▨ Cored Interval
■ Core Interval Viewed

Mobil Clarkeck

AA/10-20-090-07W4/00

KB. 444m

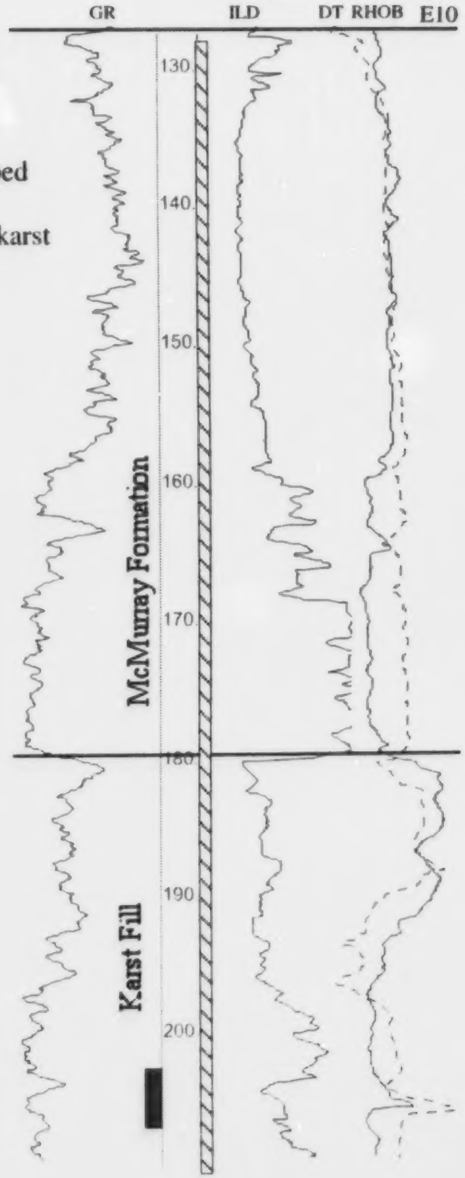
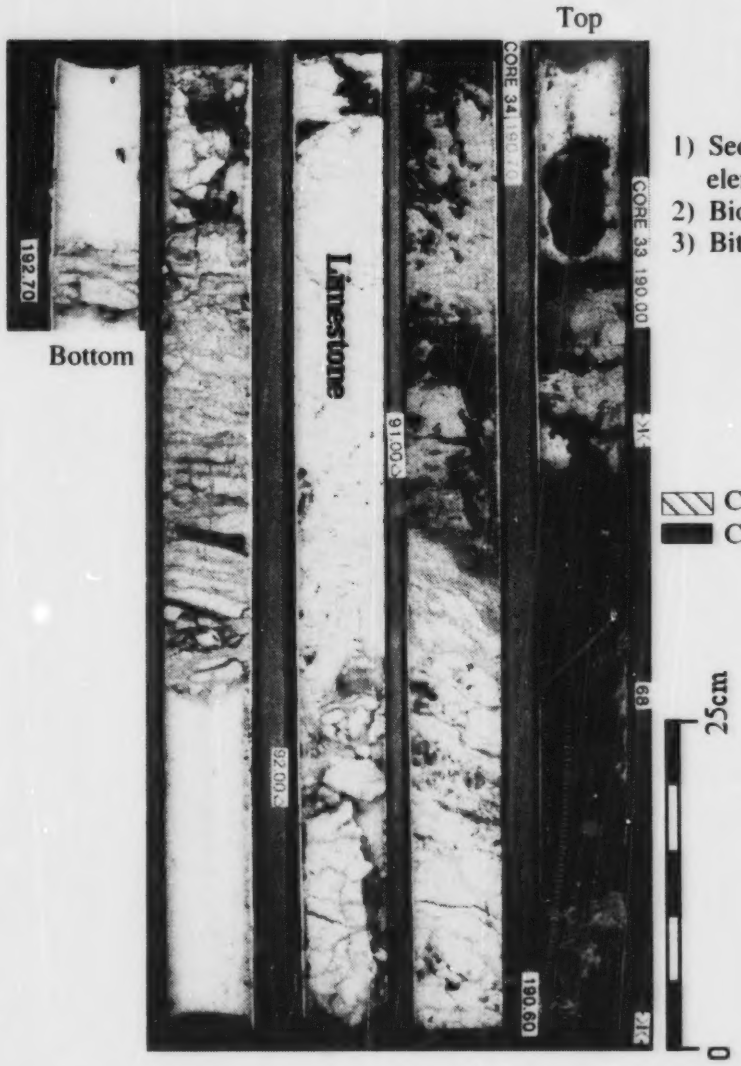


Figure 79: Interbedded and intermixed (? Slumped) carbonate (nodular white) and oil sand deposits, karst fill along the pre-Cretaceous unconformity surface, Devonian Waterways Formation interbedded with Upper McMurray sediments. Facies 18 Geophysical log response shown to the right.


Top
CORE 33 190.00
68
190.60
CORE 34 190.70
91.00
Limestone
92.00
192.70
Bottom
25cm
0

1) Sedimentary Features: slumped karst-fill elements
2) Bioturbation Index: NA
3) Bitumen Saturation: poor

▨ Cored Interval
■ Core Interval Viewed

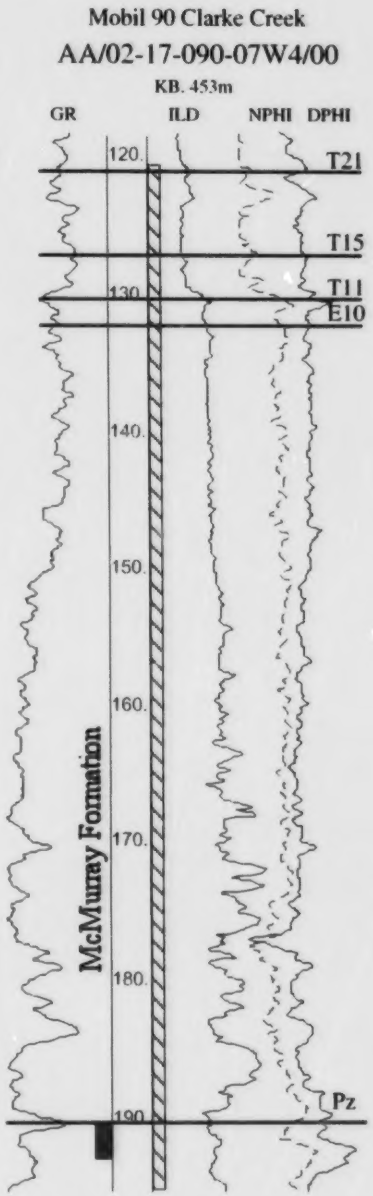


Figure 80: Slumped carbonate (nodular white) and oil sand deposits, karst-fill along the pre-Cretaceous unconformity surface. Devonian Waterways Formation interbedded with McMurray sediments. Facies 18. Geophysical log response shown to the right.

6.0 ATHABASCA OIL SANDS FACIES MODELS

6.1 Mixed Carbonate/Clastic Units Within the Karstified Region Along the pre-Cretaceous Unconformity

Paleovalleys were initiated along the pre-Cretaceous unconformity, mainly a consequence of groundwater/chemical and physical erosion of the underlying Devonian carbonates and evaporites. This resulted in an exposed karstic landscape, that infilled with mixed silici- and calci-clastic sediments along the unconformity. Paleovalleys that developed along the unconformity tend to be fairly narrow (? < 0.5 kilometre wide), deep (10's of metres), and long (? 10's of kilometres) (Figure 81). The exception is along the main trend of the Prairie Evaporite Salt Scarp where main valleys are much larger paleotopographic features.

Paleovalleys formed during a period of profound subaerial physical and chemical weathering, associated with a regional base level fall, and are correlated with events that formed the major interregional pre-Cretaceous unconformity throughout the Alberta Basin and the Western Interior Basin of the United States. The origin of the widespread interregional pre-Cretaceous unconformity is debatable, and probably lies in a combination of tectonic and eustatic controls (cf. Weimer, 1986; Dolson *et al.*, 1991). Regional slope was low at this time in northeast Alberta. Depocentres within this retroarc foreland basin setting (Miall, 1996) are far removed from mountainous source terrains for coarse clastic sediment.

Locally reservoirs in the Athabasca deposit occur along this pre-Cretaceous unconformity. Paleolows along the unconformity often contain water-bearing sands, particularly along the main valley system, associated with dissolution and collapse within the Devonian succession. These basal water-sands most likely reflect paleo-water/oil contacts that occurred in lows along the unconformity. Mixed clastic-and-carbonate paleovalley fills along the unconformity are not well connected to one another and, for the most part, would be poor reservoirs. However, the water-sands may significantly affect potential in situ steam production of overlying bitumen reservoirs if horizontal injection and production wells intersect these lows in the stratigraphic section.

Other problems with production from units along the unconformity include the occurrence of strongly cemented zones, mainly siderite, pyrite, goethite and locally quartz, that would disrupt fluid flow patterns. Mineralization along the unconformity includes massive sulphides, sphalerite, chalcopyrite, pyrite, barite, calcite, and locally gold, platinum and other precious metallic and base metals. Clays include mainly kaolinite and mixed-layer swelling clays. Kaolinite has a potential for development of migration of 'fines' problems. Siderite, pyrite and other sulphides are acid sensitive to HCl, and calcite and other silicate mineral cements are acid sensitive to HF. Barite and calcite tend to form scale with incompatible fluids, and the mixed layer clays are water sensititive and may pose potential swelling problems.

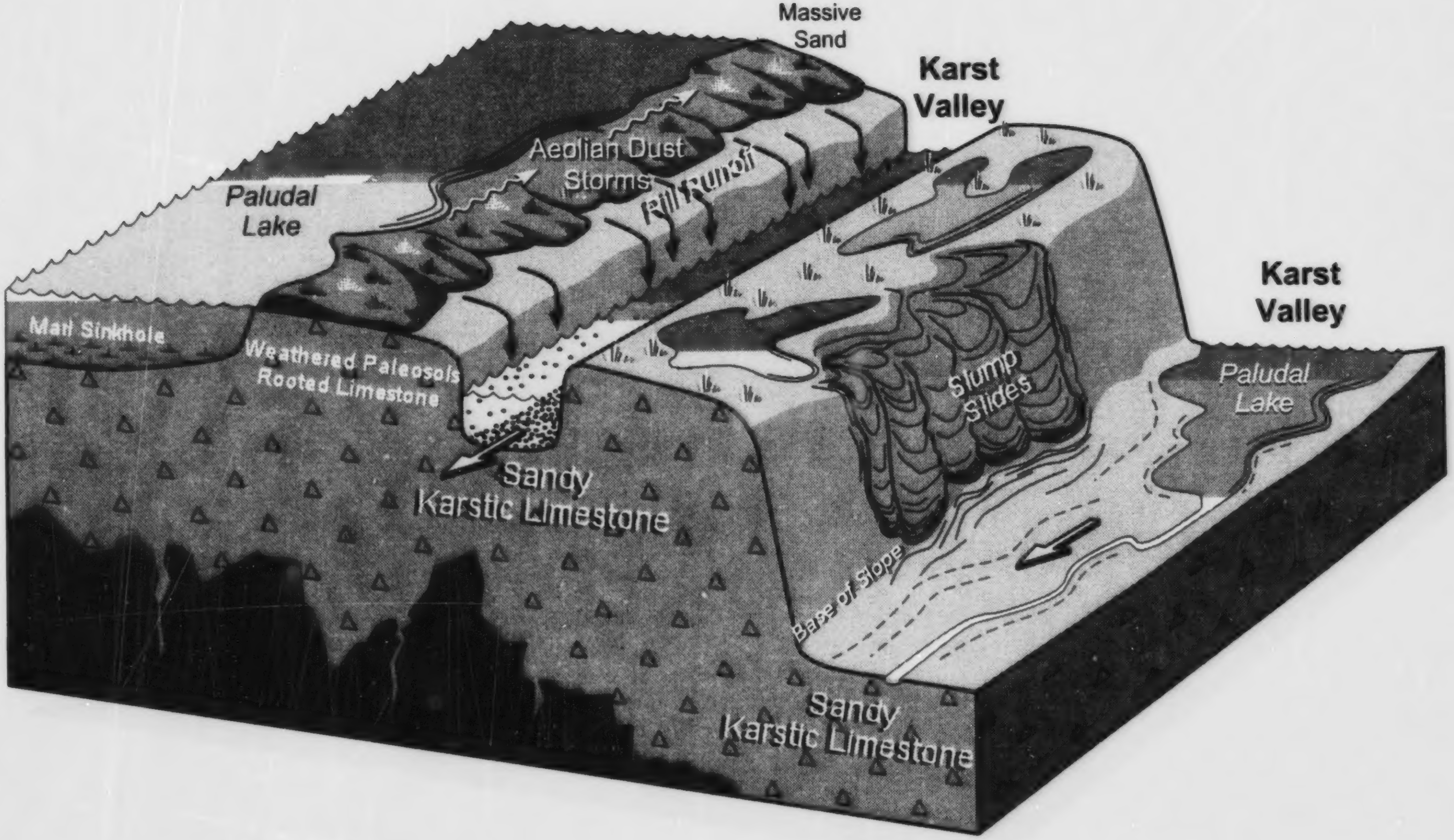

Massive
Sand
Karst
Valley
Aeolian Dust
Storms
Rill Runoff
Paludal
Lake
Marl Sinkhole
Weathered Paleosols
Rooted Limestone
Sandy
Karstic Limestone
Karst
Valley
Slump
Slides
Paludal
Lake
Base of Slope
Sandy
Karstic Limestone

Figure 81: Schematic facies model for the mixed carbonate/clastic units along the pre-Cretaceous unconformity, Athabasca deposit, northeast Alberta.

6.2 Lower McMurray Formation

The alluvial sediments of the Lower McMurray infilled the paleovalleys created along the pre-Cretaceous unconformity. Paleovalleys developed along the unconformity tend to be fairly narrow (? few kilometres wide), deep (10's of metres), and long (? 10's of kilometres) (Figure 82). The Lower McMurray hosts some of the primary reservoirs within the Athabasca deposit. These reservoirs comprise bar-and-channel sands of braided-stream complexes that were funnelled down the major paleovalleys seaward, to the north. Bordering the main channels were higher floodplain areas with bogs/swamps, likely fed by anastomozed channel systems during flood flows. Local coals and lacustrine sediments formed in the floodplain areas, that with channel migration, often became reworked and redeposited as organic detritus and mudstone intraclasts within the main channel reservoirs.

At this time regional slope increased in northeast Alberta, mainly as a consequence of a decrease in relative base level to the north. Depocentres within this retroarc foreland basin setting (Miall, 1996) received high amounts of coarse-clastic sediment bedload, mainly far-travelled derived from source terrains located to the south and west (Cant, 1998), with only local tributary input from Shield terrains to the northeast. The paleovalleys infilled with the coarse fluvial sediment as part of a regional lowstand system.

There are regional variations in the preserved thicknesses of the Lower McMurray succession. In areas with originally lower depositional gradients south of the Bitumount Basin, within the main valley system, the fluvial-dominated Lower McMurray succession is preserved as relatively thin, discontinuous units along the main paleovalley floor. To the north, along the southern margin of the Bitumount Basin, depositional gradients steepened rapidly, resulting in increased accomodation space and the availability for greater preservation potential of the Lower McMurray succession. In this region, at the seaward end of the Lower McMurray depositional system, the Lower McMurray succession hosts both estuarine and fluvial packages that internally are separated from each other by disconformities or unconformities.

The best bitumen reservoirs in the Lower McMurray Formation are the amalgamated coarse-grained, porous fluvial sediments that infilled the karstic paleovalleys. Reservoirs include the main channel sands, finer-grained braid-and side-bar/point bar deposits, and mudstone-clast breccia zones associated with main channel thalwegs along cutbanks. Amalgamated channel-and-bar complexes have very good to excellent porosity and permeability, forming sheet sands within incised, bedrock-confined paleovalleys. Minor disruptions to fluid flow within reservoir sands occur in mudstone-clast breccia zones, or where muddy valley-fills or muddy-point bars interfinger with the main braid-bar/channel sands. Reservoir sands are often capped by floodplain successions that, in general, have poor connectivity between the more isolated channel sands. The exceptions on the floodplain are the locally more extensive crevasse splay sheet sands and connected channel fills that would be good local reservoirs, within the otherwise fine-grained non-reservoir unit.

Regionally thick, apparently connected, water sands and other smaller, isolated water sands are significant within the Lower McMurray succession. Along the north-south trending main valley much of the coarse grained Lower McMurray succession is water saturated. Water sands along this particular valley often exceed 50 m thick (Flach, 1984; Wightman et *al*., 1995). These water-bearing sands, mapped at a regional scale of four wells per township, appear to be a well-connected drainage network. However, subsequent more detailed subsurface mapping has been done using a much denser well coverage in localized areas (at a scale of one well per section or down to <50-m spacing), indicating that the basal water-sands may not be as continuous and laterally correlatable as first thought. Outside the main valley trend, water-bearing sand tends to occupy localized lows on the pre-Cretaceous unconformity surface. These water sands, particularly within the main valley, may significantly affect potential in situ steam assisted bitumen production in the overlying bitumen reservoirs.

Post-depositional mineralization and clay alteration may pose problems with production from these Lower McMurray incised paleovalley reservoirs. The local occurrence of cemented zones, mainly siderite, pyrite, calcite and silica (or microcrystalline quartz), could disrupt fluid flow along these basal, porous sand reservoirs. Significant sideritization and pyrite (minor chalcopyrite) occurs within the Lower McMurray channel sands as matrix cement and as replacement of intraclasts in areas associated with sulphide mineralization along the unconformity. Clay in matrix of the Lower McMurray sands includes kaolinite and illite, both of which have a potential for migration of 'fines' problems. Siderite, calcite and pyrite are acid sensitive to HCl; and, silicate mineral cements are acid sensitive to HF. Calcite tends to form scale with incompatible fluids.

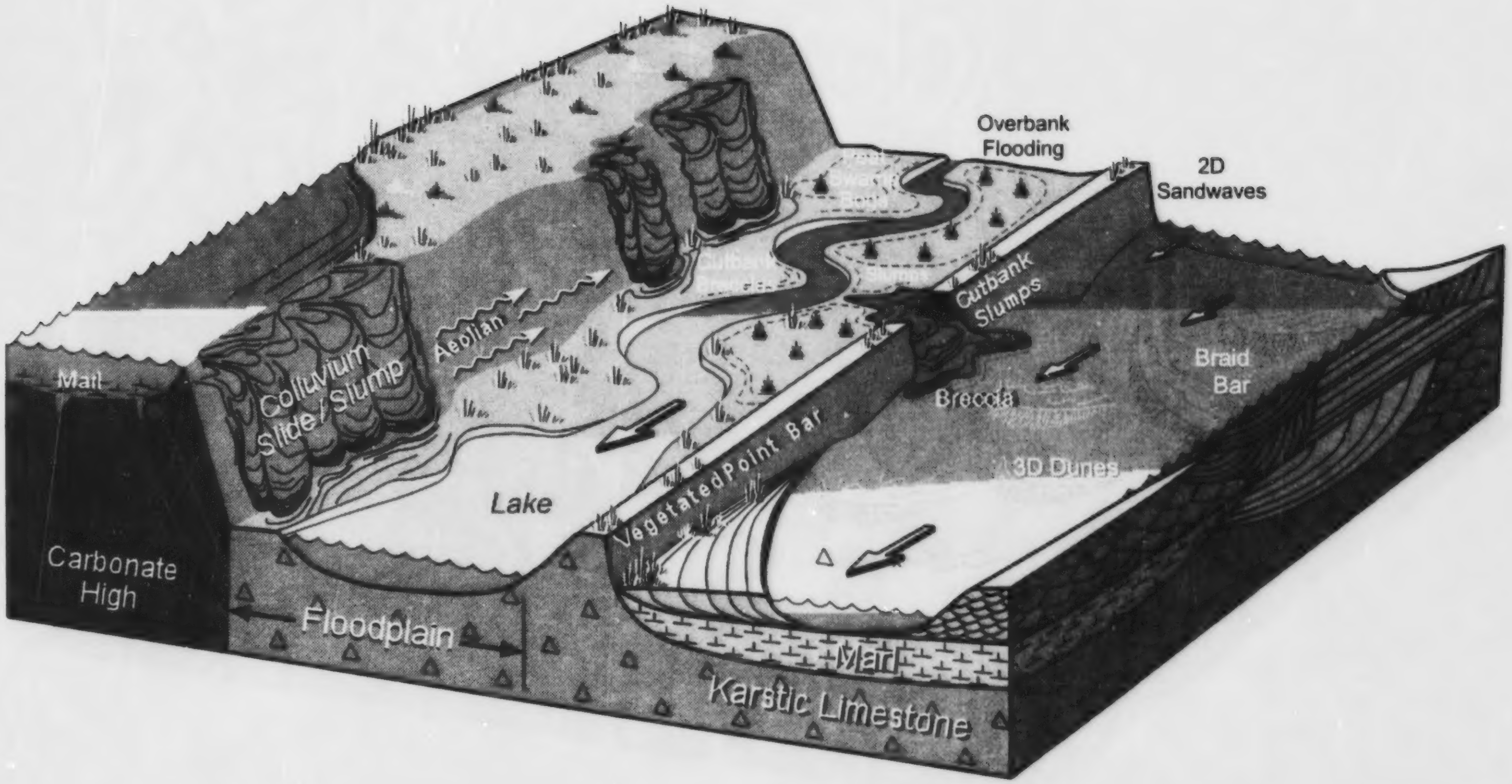

Overbank
Flooding
2D
Sandwaves
Mail
Colluvium
Slide / Slump
Aeolian
Cutbank
Breccia
Slumps
Cutbank
Slumps
Braid
Bar
Breccia
Vegetated Point Bar
3D Dunes
Lake
Carbonate
High
Floodplain
Marl
Karstic Limestone

Figure 82: Schematic facies model for the Lower McMurray Formation, Athabasca deposit, northeast Alberta.

6.3 Upper McMurray Formation

The lowermost sediments of the Upper McMurray Formation infilled and overtopped the Lower McMurray paleovalley-fills. Upper McMurray valley-fills tend to be fairly wide (<3 kilometres wide), deep (10's of metres), and long (? 10's of kilometres) (Figure 83, 84). The best reservoirs in the Upper McMurray occur within successions of stacked, amalgamated, meandering point bar-and-channel sands of estuarine complexes that are superimposed above the Lower McMurray reservoirs. Bordering the estuarine channels were higher floodplain areas with bogs/swamps, possibly fed by anastomozed channel systems during flood flows. Local coals and lacustrine sediments formed in the floodplain areas, that with channel migration, often became reworked and redeposited as organic detritus and mudstone intraclasts within the channel sands. Extensive estuarine-tidal sand, mud and mixed tidal flats developed along the channel margins, often being totally or partially removed and reworked by younger meandering channel systems.

At this time, due to an increase of relative base-level to the north, depocentres within this retroarc foreland basin setting received high amounts of mixed bedload and suspended load, as medium to fine clastic sediment, mainly far-travelled, derived from source terrains located to the south and west ((Miall, 1996; Cant, 1998). Secondary sources included tidal input from the north, and only local tributary input from Shield terrains to the northeast. The main controls on sedimentation were regional foreland basin subsidence and eustacy. It is clear that relative base level fluctuations continued throughout deposition of the Upper McMurray Formation, as indicated by the thick amalgamation of stacked estuarine channel complexes.

The best bitumen reservoirs hosted in the Upper McMurray succession occur within the amalgamated estuarine (tidally influenced) channels. Reservoir sands include fine to medium-grained, porous, tidal-estuarine channel sands; finer-grained, porous, tidal-and side-bar/point bar deposits; and, poorly sorted mudstone-clast breccia zones associated with channel thalwegs along cutbank margins. Small, isolated, water sands occur in lower and middle portions of the succession, with gas sands in upper parts of the Upper McMurray succession. These water and gas sands may significantly affect potential in situ steam assisted bitumen production from associated bitumen reservoirs (cf. AEUB 1998a, 1998b, 2000a, 2000b). For example, gas production from the reservoirs may deplete pressures such that subsequent bitumen production may be compromised. Individual channel-and-bar complexes host meandering string-shaped reservoirs. Where amalgamation has stacked thick channel-and-bar complexes sheet-shaped reservoirs occur. These sheet reservoirs differ from those of the underlying Lower McMurray braided system, with the development of internal discontinuities and clay breaks in the Upper McMurray succession. Here disruptions to fluid flow occur in mudstone-clast breccia zones, or where muddy channel fills or inclined heterolithic muddy sand interfinger or juxtapose with the channel sands. Reservoir sands are capped by muddy abandonment plugs and sandy to muddy tidal flat successions. The exceptions in the tidal flat regions are the locally more extensive crevasse splay sheet sands and sandy tidal channel (or creek) fills that could be good small scale reservoirs, within an otherwise fine-grained non-productive unit.

Problems with production from the amalgamated tidal-estuarine sand reservoirs is the common occurrence of mudstone, as breaks on inclined surfaces and as thick vertical accretion abandoned channel fills. Local cements (mainly siderite, pyrite and calcite) occur with interbedded paleosols or with brackish bay deposits. Clays in matrix of the Upper McMurray include kaolinite and illite, both of which may pose problems concerning migration of 'fines.' Siderite, calcite and pyrite are acid sensitive to HCl, and silicate mineral cements are acid sensitive to HF. Calcite tends to form scale with incompatible fluids.

In outcrops and well sites along the margin of the Bitumount Basin there is enhanced preservation of shoreface deposits within the McMurray Formation, a consequence of the E10 erosion surface bevelling off and removing most of the upper part of the McMurray further to the south (i.e. landward and farther removed from the margins of the Bitumount Basin). Two possible nearshore sands are found in McMurray outcrops. The initial interpretation is that these nearshore sands represent the preserved remnants of barrier island shoreface deposits. The first of these possible barrier island deposits is located at two outcrops along the Horse River, and the second is along the Athabasca River near Daphne Island. Preliminary descriptions of these units are presently being published in a field guide (Cotterill *et al.*, 2000) and further work is currently under way to characterize both the lithostratigraphic and biostratigraphic framework for these units.

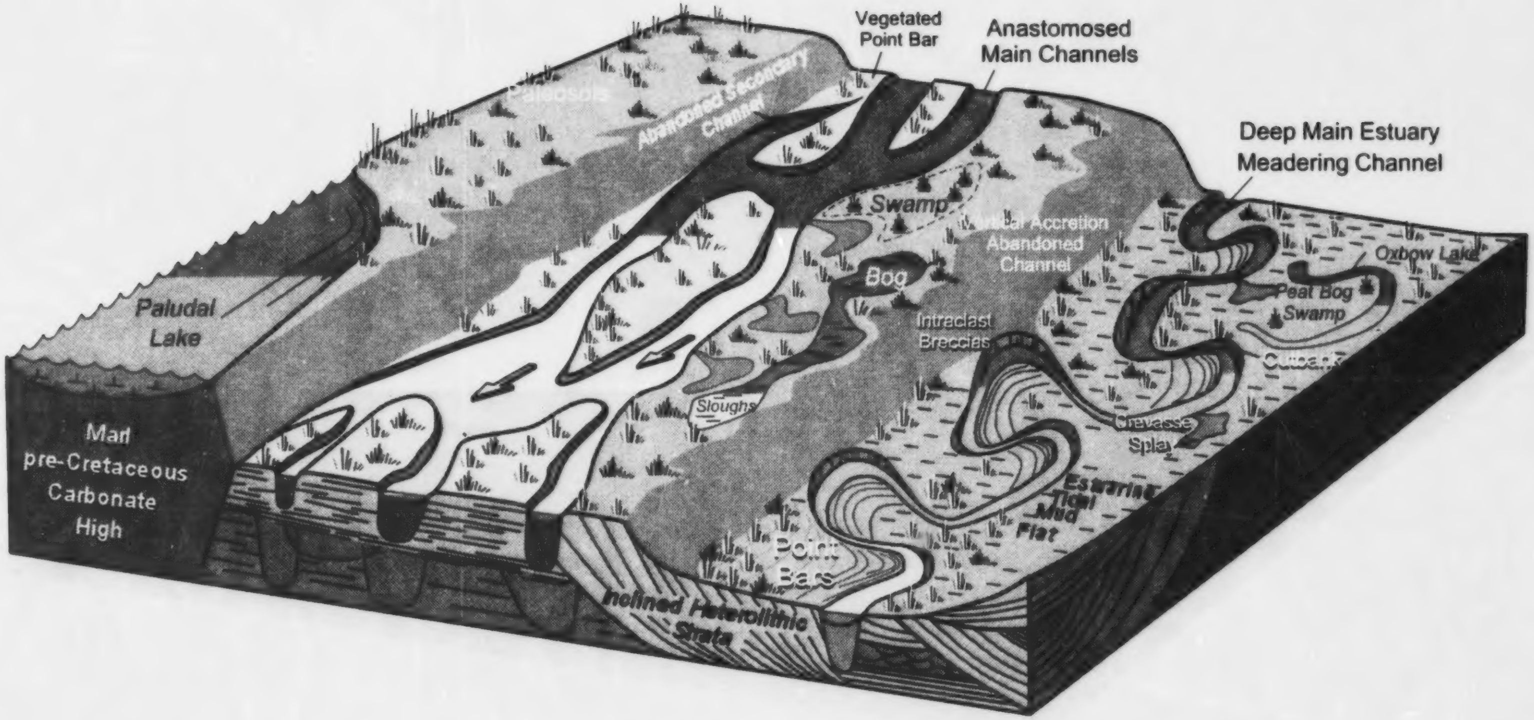

Vegetated Point Bar
Anastomosed Main Channels
Deep Main Estuary Meadering Channel
Paleosols
Abandoned Secondary Channel
Swamp
Vertical Accretion Abandoned Channel
Oxbow Lake
Peat Bog
Swamp
Bog
Paludal Lake
Intraclast Breccias
Cutbank
Sloughs
Crevasse Splay
Marl pre-Cretaceous Carbonate High
Estuarine Tidal Mud Flat
Point Bars
Inclined Heterolithic Strata

Figure 83: Schematic facies model for the lower part of the Upper McMurray Formation, Athabasca deposit, northeast Alberta.

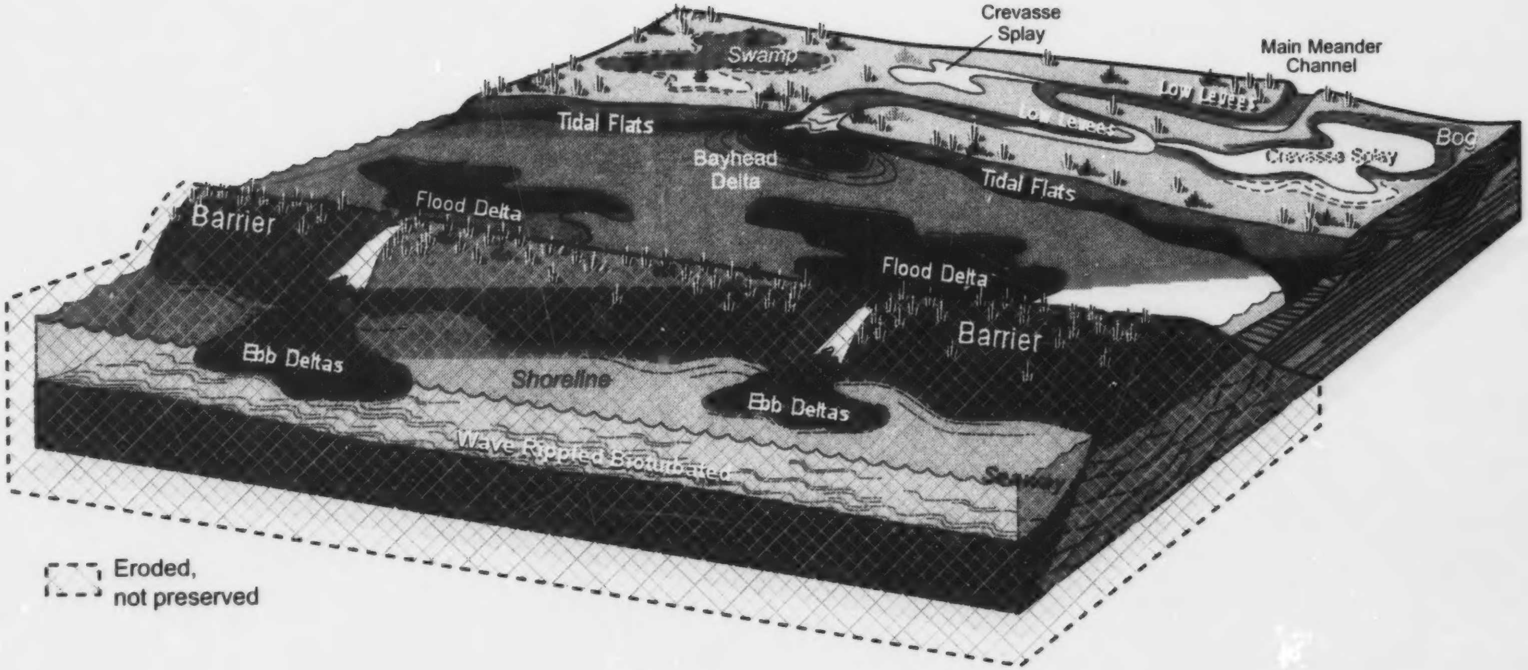

Crevasse Splay
Main Meander Channel
Swamp
Low Levees
Low Levees
Tidal Flats
Bayhead Delta
Crevasse Splay
Bog
Tidal Flats
Barrier
Flood Delta
Flood Delta
Barrier
Ebb Deltas
Shoreline
Ebb Deltas
Wave Rippled Bioturbated
Seaway
Eroded, not preserved

Figure 84: Schematic facies model for the upper part of the Upper McMurray Formation, Athabasca deposit, northeast Alberta. Most of the shoreline succession was removed during erosion associated with the unconformity between the McMurray Formation and the overlying Wabiskaw Member of the Clearwater Formation.

7.0 CONCLUSIONS

- The deposits of the McMurray Formation can be successfully identified into Lower and Upper informal members. A reassessment of the stratigraphic nomenclature with regards to informal members of the McMurray Formation indicates that the term 'Middle McMurray' should be abandoned, and any units previous assigned to the Middle McMurray are now considered parts of the Upper McMurray Formation.

- A unified lithofacies scheme has been successfully applied to the deposits examined in this study. The use of this classification scheme reduces much of the apparent heterogeneity within the Athabasca oil sands deposit, and description of lithofacies within the different informal members results in a much more understandable lithofacies pattern than was previously discerned using more complex schemes.

- Bitumen reservoirs accumulated as incised paleovalley-fills cut within the karstic pre-Cretaceous landscape, hosted within the Lower McMurray fluvial lowstand deposits. Reservoirs occur mainly within braided channel-and-bar sands and mudstone-clast breccias. Water sands within the Lower McMurray occur in paleolows along the basal pre-Cretaceous unconformity. Such water sands appear to be more prevalent in the northern extent of the Lower McMurray and may pose problems for in situ SAGD production of the oil sands as well as affecting the strategies for mining bitumen in the surface mineable areas of the Athabasca oil sands deposit.

- Bitumen reservoirs formed within estuarine valleys that are stacked above the Lower McMurray channel sands, as part of the Upper McMurray estuarine deposits. Bitumen reservoirs occur mainly within stacked estuarine-tidal channel-and-point bar complexes. Local water sands occur in the lower parts, and with gas in the upper parts of the Upper McMurray Formation.

- Bitumen-, water- and gas-reservoirs formed within prograding coastal plain, as part of the Upper McMurray estuarine and coastal plain complex.

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b) Rhythmically laminated to very thinly interbedded, rippled sand and mudstone. Sharp sand-mudstone contacts, wavy, sometimes inclined bedding. Flaser bedding prominent in upper right photo, Upper McMurray Formation. Facies 12A. Core is from Township 93, Range 12W4.

c) Rhythmically, wavy laminated to interbedded sand and mudstone with delicate, bifurcating mud laminae, commonly associated mudstone clast breccia. Facies 12B. Core from Township 93, Range 12W4.

62. Heavily bioturbated, laminated to thinly interbedded muddy sand, Upper McMurray Formation, Outcrop #3, Steepbank River. Facies 12B.

63. Heavily bioturbated, laminated/ thinly interbedded, muddy sand and mudstone (Facies 12B), with minor flaser interbeds (Facies 9B), Upper McMurray Formation. Facies 12B, 9B. Geophysical log response shown to the right. Core AO-90, AE/01-18-093-12W4.

64. Heavily bioturbated, laminated/ thinly interbedded, sandy mud, Upper McMurray Formation. Facies 12C. Geophysical log response shown to the right. Core Mobil 90 Clarke Creek, AA/02-08-090-07W4/00.

65. Variably bioturbated, laminated/ thinly interbedded, silty mudstone and mudstone, Upper McMurray Formation. Facies 12D. Geophysical log response shown to the right. Core Mobil 90 Clarke Creek, AA/10-08-090-07W4/00.

66. Thinly laminated/interbedded, silty mudstone and mudstone, showing minor bioturbation, Upper McMurray Formation. Facies 12E. Geophysical log response shown to the right. Core Mobil 90 Clarke Creek, AA/03-05-090-07W4/00.

67. Thinly laminated/interbedded, silty mudstone and mudstone, showing minor bioturbation, Upper McMurray Formation. Facies 12E. Geophysical log response shown to the right. Core Mobil Clarke Creek, AA/10-20-090-07W4/00.

68. Burrow-mottled (churned) muddy sand with rare primary stratification and bedding preserved, Upper McMurray Formation. Facies 13A. Geophysical log response shown to the right. Core AO-81, AB/01-18-093-12W4.

69. Burrow-mottled (churned) sandy mud with some primary stratification and flaser-bedding preserved, Upper McMurray Formation, unconformably overlain by burrowed, wavy-bedded Wabiskaw Member sediments (arrow). Facies 13B. Geophysical log response shown to the right. Core AO-66, AB/09-18-093-12W4.

70. Rooted (arrows) siltstone, Upper McMurray Formation, Outcrop #9-2, Steepbank River. Facies 14.

71. Rooted (arrows) muddy sand, capped by burrowed sandy siltstone, Upper McMurray Formation, 25-metre level in section #2, Outcrop #9, Steepbank River. Facies 14.

72. Carbonaceous muddy sand, alternating with coaly interlaminae, Upper McMurray Formation. Facies 14. Geophysical log response shown to the right. Core Mobil Clarke, AA/12-34-89-08W4/00.

73. Coarsening-upward units of mud-silt-sand. Facies 15. Geophysical log response shown to the right. Core AO-93, AC/06-18-093-12W4.

74. Wave-rippled, very fine to fine grained sand, bedding plane top view, showing sinuous, out-of-phase wave-ripples, Upper McMurray Formation, Ells River. Facies 16.

75. Wave-rippled, very fine to fine grained sand, showing sinuous, out-of-phase wave-ripples, in cross section, Upper McMurray Formation, Ells River. Facies 16.

76.
   a) Map showing location of the Beaver River sandstone quarry, Fort MacKay.

   b) Detailed location map and stratigraphic section of the Beaver River sandstone quarry, Fort MacKay. Site designations refer to historical archaeological sites in the area (diagram courtesy of Mark Fenton of the Alberta Geological Survey).

77. Weathered nodular carbonate at the pre-Cretaceous unconformity, indicated by arrow, overlain by carbonaceous to coaly silty mudstone (Facies 3) and rooted, very fine to fine silty/sandy mudstone (Facies 4), Devonian Waterways Formation overlain by Lower McMurray Formation. Core 03-28-096-16W4.

78. Thin, laminated carbonate overlain by karst-infill of slumped and trough cross-bedded, pebbly sand and gravel (Facies 1, 2, 7B), Devonian Waterways Formation overlain by Lower McMurray Formation. Geophysical log response shown to the right. Core Mobil 90 Clarke Creek, AA/01-05-090-07W4.

79. Interbedded and intermixed (? slumped) carbonate (nodular white) and oil sand deposits, karst-fill along the pre-Cretaceous unconformity surface, Devonian Waterways Formation interbedded with Upper McMurray sediments. Facies 18. Geophysical log response shown to the right. Core Mobil Clarke Creek, AA/10-20-090-07W4/00.

80. Slumped carbonate (nodular white) and oil sand deposits, karst-fill along the pre-Cretaceous unconformity surface. Devonian Waterways Formation interbedded with McMurray sediments. Facies 18. Geophysical log response shown to the right. Core Mobil 90 Clarke Creek, AA/02-17-090-07W4/00.

81. Schematic facies model for the mixed carbonate/clastic units along the pre-Cretaceous unconformity, Athabasca deposit, northeast Alberta.

82. Schematic facies model for the Lower McMurray Formation, Athabasca deposit, northeast Alberta.

83. Schematic facies model for the lower part of the Upper McMurray Formation, Athabasca deposit, northeast Alberta.

84. Schematic facies model for the upper part of the Upper McMurray Formation, Athabasca deposit, northeast Alberta. Most of the shoreline succession was removed during erosion associated with the unconformity between the McMurray Formation and the overlying Wabiskaw Member of the Clearwater Formation.

Mining

Sponsor	Project	Investment	New Capacity	Startup	Deposit
Koch Oil Sands LP, United Tristar Resources	Fort Hills	$1 billion	90,000 bpd	2004	Athabasca
Mobil Oil Canada	Kearl Mine	$1 billion	130,000 bpd	2003	Athabasca
Mobil Oil Canada	Upgrader	$1-$1.5 billion	130,000 bpd	2003	Athabasca
Shell Canada	Muskeg River Mine	$1.2 billion	150,000 bpd	2002	Athabasca
Shell Canada	Corridor Pipeline	$375 million	200,000 bpd	2002	Athabasca
Shell Canada	Scotford Upgrader	$1.8 billion	150,000 bpd	2002	Athabasca
Suncor Energy	Fort McMurray Plant	$200 million	emissions cuts	complete	Athabasca
Suncor Energy	Upgrader expansion	$320 million	27,400 bpd	1997-2001	Athabasca
Suncor Energy	Steepbank Mine	$360 million	n.a.	1997-2001	Athabasca
Suncor Energy	Millennium	$190 million	25,000 bpd	1997-2001	Athabasca
Suncor Energy	Millennium	$2 billion	80,000 bpd	1999-2002	Athabasca
Syncrude Canada	North Mine	$500 million	22,000 bpd	1999	Athabasca
Syncrude Canada	Aurora Mine	$1.5 billion	117,000 bpd	1998-2004	Athabasca
Syncrude Canada	Continuous improvement	$1 billion	n.a.	1997-2007	Athabasca
Syncrude Canada	Upgrading Expansion	$3 billion	138,000 bpd	1999-2007	Athabasca

In Situ – Underground extraction

Sponsor	Project	Investment	New Capacity	Startup	Deposit
Alberta Energy Co.	Foster Creek	$213 million	30.000 bpd	2000	Cold Lake
AEC pipelines	Alberta Oil Sands Pipeline	$220 million	300.000 bpd	1999	Athabasca
AEC pipelines, Husky Oil	Lakeline Pipeline	$400 million	150.000 bpd	2000	Athabasca
Alberta Energy (Amber Energy acquisition)	Pelican Lake	$300 million	9.000 bpd	1999	Athabasca
Alberta Energy (Amber Energy acquisition)	Pelican Lake Pipeline	$47 million	150,000 bpd	1999	Athabasca
Alberta Energy Co.	Frog Lake	$12 million	2,800 bpd	complete	Cold Lake
ATCO Electric (Alberta Power)	Suncor Powerlines	$6 million	n.a.	complete	Athabasca
Blackrock Ventures	Cold Lake	$8 million	600 bpd	n.a.	Cold Lake
BP Amoco Canada	Primrose-Wolf Lake	$675 million	55,000 bpd	2000+	Cold Lake
BP Amoco Canada	Brintnell	$100 million	15,000 bpd	2000	Athabasca
Canada Oil Sands Co.	Hangingstone	$197 million	10.000 bpd	2004	Athabasca
Canadian Natural Resources	Beartrap and Charlotte Lakes	$800 million	20.000 bpd	2002	Cold Lake
Canadian Natural Resources	Pelican Lake	(included in Beartrap)	60.000 bpd	2002	Athabasca
Enbridge Inc.	Wild Rose Pipeline	$325 million	500.000 bpd	complete	Athabasca
Gulf Canada Resources	Surmont	$1.1 million	100.000 bpd	2008	Athabasca
Husky Oil	Lloydminster BiProvincial Upgrader	$500 million	80.000 bpd	n.a.	all
Imperial Oil	Cold Lake 1-10 Pad Phases	$250 million	30,000 bpd	in progress	Cold Lake
Imperial Oil	Cold Lake Mahkeses (Phases 11-13)	$550 million	30.000 bpd	2001	Cold Lake
Imperial Oil	Cold Lake Phases 14-15	$300 million	n.a.	2001	Cold Lake
Imperial, BP Amoco and Koch Canada	ThickSilver Pipeline	$250 million	330.000 bpd	2001	Cold Lake
Koch Oil Sands LP	Elk Point	$200 million	40.000 bpd	ongoing	Cold Lake
Koch Pipelines LP	Hardisty Crude Terminal	$35-40 million	650.000 bbl storage	1999	all
Mobil Oil Canada	Bonnyville-Iron River	$16 million	54-well test	ongoing	Cold Lake
Murphy Oil Co.	Lindbergh	$157 million	n.a	1999	Cold Lake
Norman Energy Resources	Cold Lake, Provost, Lindbergh	$300-400 million	n.a.	ongoing	Cold Lake
Northstar Energy	Dover Project	$10 million	3.000 bpd	complete	Athabasca
Nova Gas Canada	Suncor Fort McMurray	$164 million	Byproduct plant	1999	Athabasca
Numac Energy	Manalokan (pilot plant)	$57 million	n.a.	ongoing	Cold Lake
PanCanadian Petroleum	Elk Point, Lindbergh, Frog Lake, Marwayne	$100 million+	4,500+ bpd	ongoing	Cold Lake
PanCanadian Petroleum (CS acquisition)	Christina Lake	$250 million	50.000 bpd	2000	Athabasca
Petro Canada	McKay River	$210 million	20.000 bpd	2007	Athabasca
Ranger Oil (Elan Energy acquisition)	Lindbergh, Elk Point, Wolf Lake, Cold Lake	$225 million	10,000+ bpd	ongoing	Cold Lake
Shell Canada	Peace River	$163 million	12.000 bpd	2002	Peace River
Suncor Energy Inc.	Primrose-Burnt Lake	Up to $122 million	Up to 12.5 00 bpd	pilot, ongoing	Cold Lake
Texaco Canada Petroleum	Frog Lake	$35 million	n.a.	pilot	Cold Lake

Appendix 1: Oil Sands Developments (Oilweek Magazine, August 2, 1999)

Appendix 2. Definition of Picks and Quality Codes from Athabasca Oil Sands DataBase (Wynne *et al.*, 1994)

Pick	Type of Surface	Description	Average Quality Code
Mannville	Disconformity	Top of Mannville	Very Good
T61	Transgressive	Top of Clearwater A	Very Good
T51	Transgressive	Marker below Clearwater A	Good
T41	Transgressive	Top of Clearwater B	Poor to Very Poor Regionally Not Picked
T31	Transgressive	Top of Clearwater C	Good
T21	Transgressive	Top of Wabiskaw A	Good to Very Good
T 15	Transgressive	Top of Wabiskaw B	Good to Very Good
E14	Erosional	Incision during Wabiskaw	Good to Very Good
T11	Transgressive	Base of First Regional Marine Shale; Top of.Wabiskaw C	Very Good to Excellent
T10.5	Transgressive	Top Incised Valley-Fill; Top of Wabiskaw D	Excellent to Very Good
E10	Disconformity/ Unconformity	Major Erosion Surface Top of McMurray Fm.	Excellent to Very Good
E10.5	Disconformity	Major Erosion Surface Top of Lower McMurray Fm	Variable, Excellent to Poor
McMurray		Top of McMurray Fm	Excellent to Very Good
Sub-Cret.	Unconformity	Major Erosion Surface Base of McMurray Fm.	Variable, Excellent to Poor

Appendix 3. List of Core and Outcrop Locations Used in the Present Study

List of Measured Stratigraphic Sections in the Study Area by UTM designations for eastings and northings and 1:50 000 scale topographic map reference numbers (# refer to the number portions of the text).

#	Name of Section	River	Map #	Map Name	Easting	Northing
6.1	Amphitheatre #2	MacKay	74E/4	Fort MacKay	0459970E	6338850N
6.1	Amphitheatre #1	MacKay	74E/4	Fort MacKay	0459900E	6338820N
6.1	Amphitheatre #1A	MacKay	74E/4	Fort MacKay	0459850E	6338750N
6.2	Viewpoint	MacKay	74E/4	Fort MacKay	0459990E	6339151N
6.3	Gauging Station #2	MacKay	74E/4	Fort MacKay	0457754E	6341550N
6.4	Gauging Station #1	MacKay	74E/4	Fort MacKay	0457473E	6341450N
6.5	MacKay Karst #1&2	MacKay	74E/4	Fort MacKay	0459500E	6338650N
6.6	MacKay Karst #3	MacKay	74E/4	Fort MacKay	0459500E	6338450N
6.7	MacKay River West	MacKay	74E/4	Fort MacKay	0454700E	6336490N
6.8	Sandstone Quarry	Beaver	74E/4	Fort MacKay	0462350E	6330850N
7.1	Ells 99-01	Ells	74E/5	Bitumount	0458550E	6351300N
7.2	Ells 99-02	Ells	74E/5	Bitumount	0458500E	6351200N
7.3	Ells 99-03	Ells	74E/5	Bitumount	0458450E	6351050N
7.4	Ells 99-04	Ells	74E/5	Bitumount	0458750E	6350875N
7.5	Ells 99-05	Ells	74E/5	Bitumount	0458600E	6350800N
7.6	Ells 99-06	Ells	74E/5	Bitumount	0454750E	6343300N
7.7	Ells 99-07	Ells	74E/5	Bitumount	0454760E	6343310N
7.8	Ells 99-08	Ells	74E/5	Bitumount	0455100E	6343580N
7.9	Ells 99-09	Ells	74E/5	Bitumount	0455000E	6343500N
7.10	Ells 99-10	Ells	74E/5	Bitumount	0455130E	6343550N
7.11	Ells 99-11	Ells	74E/5	Bitumount	0455200E	6343380N
8.1	Saline Creek #1	Saline Ck.	74D/11	Fort McMurray	0478730E	6283383N
8.1	Saline Creek #2	Saline Ck.	74D/11	Fort McMurray	0478730E	6283480N
8.1	Saline Creek #3	Saline Ck.	74D/11	Fort McMurray	0478740E	6283550N
8.1	Saline Creek #4	Saline Ck.	74D/11	Fort McMurray	0478825E	6283721N
8.2	Hangingstone #1	Hangingstone	74D/11	Fort McMurray	0477530E	6284570N
8.2	Hangingstone #2	Hangingstone	74D/11	Fort McMurray	0478100E	6284600N
8.3.1	Horse #1	Horse	74D/11	Fort McMurray	0475560E	6285050N
8.3.2	Horse #2	Horse	74D/11	Fort McMurray	0476070E	6284520N
8.3.3	Horse #3	Horse	74D/11	Fort McMurray	0475550E	6283820N
8.3.4	Horse #4	Horse	74D/11	Fort McMurray	0476200E	6285050N
9.1	Daphne Is. East #5	Athabasca	74E/5	Bitumount	0460210E	6350433N
9.1	Daphne Is. East #4	Athabasca	74E/5	Bitumount	0460230E	6350370N
9.1	Daphne Is. East #3	Athabasca	74E/5	Bitumount	0460250E	6350300N
9.1	Daphne Is. East #2	Athabasca	74E/5	Bitumount	0460220E	6350200N
9.1	Daphne Is. East #1	Athabasca	74E/5	Bitumount	0460230E	6350120N
9.2	Daphne Is. West #3	Athabasca	74E/5	Bitumount	0459650E	6349002N
9.2	Daphne Is. West #2	Athabasca	74E/5	Bitumount	0459640E	6349110N
9.2	Daphne Is. West #1	Athabasca	74E/5	Bitumount	0459630E	6349200N
9.3	Fluvial Marl	Athabasca	74E/5	Bitumount	0474746E	6305612N
9.4	Tar Island	Athabasca	74D/14	Wood Creek	0472210E	6313710N

9.5	McMurray Fm. Type	Athabasca	74D/11	Fort McMurray	0476166E	6291550N
10.1	Steepbank #3-1	Steepbank	74E/3	Hartley Creek	0473675E	6319100N
10.1	Steepbank #3-2	Steepbank	74E/3	Hartley Creek	0473700E	6319070N
10.1	Steepbank #3-3	Steepbank	74E/3	Hartley Creek	0473725E	6319050N
10.2	Steepbank #4-1	Steepbank	74E/3	Hartley Creek	0473600E	6318860N
10.2	Steepbank #4-2	Steepbank	74E/3	Hartley Creek	0473550E	6318800N
10.3	Steepbank #7	Steepbank	74E/3	Hartley Creek	0474440E	6318110N
10.4	Steepbank #9-1	Steepbank	74E/3	Hartley Creek	0475300E	6317760N
10.4	Steepbank #9-2	Steepbank	74E/3	Hartley Creek	0475400E	6317700N
10.4	Steepbank #9-3	Steepbank	74E/3	Hartley Creek	0475370E	6317610N
10.5	Steepbank #10	Steepbank	74D/14	Hartley Creek	0475700E	6317250N
11.1	Christina #1	Christina	74D/11	Fort McMurray	0498075E	6278050N

FACIES WELLS

UWI	LAT	LONG	Kelly Bushing	Ground Elevation	Final Formation
00/11-09-079-15W4/0	55.83182	112.2911	630.9	627	DEV
00/03-32-080-07W4/0	55.9724	111.06194	636.1	633.9	BH LK
AA/07-26-080-11-W4/0	55.96072	111.60659	688.8	685.8	BH LK
00/05-24-080-23-W4/0	55.94581	113.47223	587.7	583	MCM
00/06-36-082-12-W4/0	56.14967	111.74351	747.4	744	PRECAMB
00/01-11-082-23-W4/0	56.0879	113.47943	614.7	611.1	DEV
00/07-11-082-25-W4/0	56.09146	113.79895	583.1	580	WAB
00/07-16-083-07-W4/0	56.19363	111.04219	715.6	711.2	FIREBAG
AA/13-24-084-11W4/0	56.3033	111.60509	579.1	576	DEV
00/13-27-084-11-W4/0	56.31736	111.65776	563.2	559.7	DEV
AA/05-15-085-07W4/0	56.36808	111.02873	474.6	473.4	BH LK
00/07-04-085-23-W4/0	56.34052	113.56915	576.1	572.4	CALMAR
03/05-02-086-07-W4/0	56.42542	111.0038	480.8	477.5	DEV
AA/06-13-087-07W4/0	56.54322	110.97791	438.4	436.9	BH LK
AA/09-31-087-08W4/0	56.58995	111.25758	395.9	392.8	
AA/10-11-087-16W4/0	56.53146	112.43319	503.3	499.7	L IRE
AA/10-03-088-06W4/0	56.60516	110.86542	430.2	427.2	
AA/04-08-089-07W4/0	56.69958	111.09001	423.7	422.5	BH LK
AA/16-19-089-07W4/0	56.73863	111.09786	429.5	428.2	BH LK
AA/12-34-089-08W4/0	56.7644	111.19738	418.1	415.1	BH LK
AA/07-14-089-09W4/0	56.71881	111.31407	356.9	355.7	BH LK
AA/12-14-089-10W4/0	56.719	111.48705	368	368	
AA/06-20-089-10W4/0	56.73144	111.56271	397.3	397.3	
AA/11-07-090-07W4/0	56.79321	111.11084	453.2	453.2	NONE IDEN
AB/10-21-090-07W4/0	56.82234	111.05118	447.7	447.7	NONE IDEN
AA/12-09-090-08W4/0	56.79416	111.22331	413.4	410.6	BH LK
AA/01-23-090-10W4/0	56.81345	111.47249	346.8	346.8	BH LK
AA/04-01-091-08W4/0	56.85872	111.15507	444.1	444.1	BH LK
AA/03-20-091-08W4/0	56.90106	111.25275	431.3	431.3	BH LK
AA/01-30-091-08W4/0	56.9157	111.26637	429.8	429.8	BH LK
AA/16-26-091-09W4/0	56.92931	111.31959	361.8	360.6	MCM
AA/06-16-091-13W4/0	56.89274	112.03363	449.3	445.9	BH LK
AA/12-08-091-14W4/0	56.88068	112.22802	478.5	475.5	BH LK
AA/10-26-091-15W4/0	56.9244	112.2953	477.2	474.2	BH LK
AA/10-08-091-17W4/0	56.88067	112.69789	509.2	505.6	L IRE
AA/16-23-092-08W4/0	57.00218	111.15902	457.5	456.3	BH LK
AA/03-01-092-09W4/0	56.94565	111.31198	367.8	367.8	BH LK
AA/01-09-092-09W4/0	56.9621	111.37663	343.6	343.6	BH LK
AA/12-15-092-09W4/0	56.98399	111.36655	339.3	339.3	BH LK
AA/02-16-092-09W4/0	56.97651	111.38331	342.4	341	BH LK
AA/05-30-092-09W4/0	57.00642	111.45236	246.4	245	BH LK
AA/05-33-092-09W4/0	57.02403	111.39365	345.3	345.3	BH LK
AA/08-03-092-10W4/0	56.9484	111.50798	328.9	320	BH LK
AB/10-34-092-10W4/0	57.026	111.51626	304.8	304.8	BH LK

FACIES WELLS

UWI	LAT	LONG	Kelly Bushing	Ground Elevation	Final Formation
AA/01-12-092-12W4/0	56.96114	111.78111	393.8	393.8	
AA/04-17-092-12W4/0	56.97653	111.90836	392.3	387.2	BH LK
AA/01-24-092-12W4/0	56.99069	111.78098	370.9	370.9	BH LK
AA/15-26-092-12W4/0	57.01362	111.81094	365.5	365.5	BH LK
AA/09-20-092-13W4/0	56.99611	112.04882	473	473	
AA/10-23-092-13W4/0	56.99611	111.97124	440.6	440.6	
AA/10-26-092-16W4/0	57.01164	112.45634	478.5	476.4	WOODBEND
AA/10-18-093-06W4/0	57.07041	110.95204	550.5	547.8	BH LK
AA/10-12-093-07W4/0	57.05515	110.98076	521.5	520	BH LK
AA/04-14-093-07W4/0	57.06259	111.02083	509.6	508.1	BH LK
AA/11-18-093-07W4/0	57.06981	111.12156	487.4	485.9	BH LK
AA/02-21-093-07W4/0	57.07705	111.06122	508.1	506.6	BH LK
AA/10-24-093-07W4/0	57.08425	110.98075	534	532.5	BH LK
AA/12-36-093-07W4/0	57.1134	110.99397	536.8	535.2	BH LK
AA/04-28-093-09W4/0	57.09169	111.39629	336.3	336.3	BH LK
AB/06-09-093-10W4/0	57.05313	111.54981	316.2	316.2	BH LK
AA/01-20-093-10W4/0	57.0753	111.5658	286.2	286.2	BH LK
AB/16-03-093-11W4/0	57.04281	111.67248	314.4	314.4	BH LK
AA/06-06-093-11W4/0	57.03572	111.76594	347.4	347.4	
AA/01-22-093-11W4/0	57.07729	111.67422	318.6	318.6	BH LK
AA/01-32-093-11W4/0	57.10543	111.72723	328.8	328.8	BH LK
AA/01-33-093-11W4/0	57.10762	111.69629	325.6	325.6	BH LK
AA/07-29-093-13W4/0	57.09553	112.05274	372.7	372.7	
AA/10-08-093-17W4/0	57.05525	112.69798	509.9	506.3	WOODBEND
AA/11-07-094-06W4/0	57.14163	110.96229	550.6	547.5	
AA/09-19-094-06W4/0	57.17224	110.94907	561.9	558.8	
AA/10-27-094-07W4/0	57.18642	111.03389	522.6	522.6	BH LK
AA/03-30-094-07W4/0	57.17899	111.11962	452.1	452.1	BH LK
AA/08-29-094-08W4/0	57.18254	111.24234	361.1	361.1	BH LK
AA/12-16-094-09W4/0	57.15707	111.39629	326.1	326.1	BH LK
AA/09-11-094-10W4/0	57.14248	111.48368	316.7	316.7	BH LK
AA/14-15-094-10W4/0	57.16253	111.52565	308.5	308.5	BH LK
AA/07-26-094-10W4/0	57.18258	111.49038	308.4	308.4	BH LK
AA/03-33-094-10W4/0	57.19371	111.55109	281.5	281.5	BH LK
AA/01-07-094-12W4/0	57.13609	111.91537	352.4	352.4	BH LK
AA/02-12-094-12W4/0	57.13538	111.78687	329.3	329.3	BH LK
AA/10-08-094-14W4/0	57.14253	112.21423	434	428.8	BH LK
AA/16-30-094-15W4/0	57.18961	112.39839	523.7	523.7	BH LK
AA/10-11-094-16W4/0	57.13889	112.46312	504.7	501.1	BH LK
AA/05-26-095-01W4/0	57.27074	110.05725	487.7	487.7	BH LK
AA/05-11-095-07W4/0	57.22619	111.0314	503.9	502.9	MCM
AA/04-03-095-08W4/0	57.20807	111.2211	365.4	365.4	BH LK
AA/16-07-095-08W4/0	57.2334	111.28216	330.2	330.2	BH LK
AA/13-08-095-08W4/0	57.23338	111.27509	331.1	331.1	BH LK

FACIES WELLS

UWI	LAT	LONG	Kelly Bushing	Ground Elevation	Final Formation
AA/16-07-095-08W4/0	57.2334	111.28216	330.2	330.2	BH LK
AA/13-08-095-08W4/0	57.23338	111.27509	331.1	331.1	BH LK
AA/07-10-095-09W4/0	57.22531	111.36908	317.2	317.2	BH LK
AA/15-31-095-10W4/0	57.29001	111.61066	293	293	BH LK
AA/12-26-095-11W4/0	57.27414	111.68478	289.9	288.3	BH LK
AA/16-30-095-11W4/0	57.27857	111.76709	306	304.5	BH LK
AA/04-20-095-12W4/0	57.25037	111.92726	347.8	347.8	BH LK
AA/01-22-095-12W4/0	57.2503	111.84815	328	326.4	BH LK
AA/01-23-095-12W4/0	57.25033	111.82117	325.8	324.3	BH LK
AA/01-21-095-12W4/0	57.25027	111.87513	336.5	334.7	BH LK
AA/09-24-095-12W4/0	57.25754	111.79423	317.9	317.9	BH LK
AA/01-27-095-12W4/0	57.26484	111.8482	331	329.8	BH LK
AA/01-01-096-07W4/0	57.29556	110.98427	490.1	488.7	BH LK
AA/16-07-096-08W4/0	57.32076	111.28512	298.1	298.1	MCM
AA/09-12-096-08W4/0	57.31702	111.14673	340.5	338.9	BH LK
AA/04-07-096-09W4/0	57.3112	111.46626	296.4	296.4	BH LK
AA/03-02-096-10W4/0	57.29698	111.51447	300.5	300.5	BH LK
AA/14-30-096-10W4/0	57.36609	111.61714	288.4	288.4	MCM
AA/09-02-096-12W4/0	57.30243	111.82135	322.5	321	BH LK
AA/09-03-096-12W4/0	57.3012	111.84839	327.4	325.8	BH LK
AA/06-08-096-14W4/0	57.31505	112.24433	562.7	559.7	BH LK
AA/03-02-096-15W4/0	57.29578	112.32199	580.7	577.3	BH LK
AA/08-18-096-16W4/0	57.3277	112.57956	651.5	647.9	BH LK
AA/03-28-096-16W4/0	57.35439	112.54076	658.8	655.4	BH LK
AA/04-08-098-12W4/0	57.48287	111.92198	516.5	513.2	BH LK
AA/16-21-098-13W4/0	57.52283	112.04143	793.6	790.3	
AA/11-26-099-15W4/0	57.6219	112.34852	727.9	724.5	
AA/06-31-101-12W4/0	57.80769	111.96491	792.2	788.8	BH LK
AA/13-31-103-12W4/0	57.98953	111.99303	342.9	342.9	

FACIES WELLS

UWI	Total Depth	Well Name
00/11-09-079-15-W4/0	460	BVX ET AL PORTAGE 11-9
00/03-32-080-07-W4/0	433	CWWE CHARD 3-32
AA/07-26-080-11-W4/0	482.2	ARCO ACI MCMURRAY OV 7-26
00/05-24-080-23-W4/0	444	AMOCO BRINTNELL EX 5-24
00/06-36-082-12-W4/0	1080.5	R O CORP ET AL DIVIDE 6-36
00/01-11-082-23-W4/0	443	AMOCO BRINTNELL 1-11
00/07-11-082-25-W4/0	454.5	CGGS AMOCO HOOLE 7-11
00/07-16-083-07-W4/0	545	GULF RESDELN 7-16
AA/13-24-084-11-W4/0	342	PCI PCEJ HANGST OV 13-24
00/13-27-084-11-W4/0	328	PCI PCEJ HANGST EX 13-27
AA/05-15-085-07-W4/0	273.7	AMOCO C-33 GREGOIRE OV 5-15
00/07-04-085-23-W4/0	426.7	CHEVRON ET AL WABASCA 7-4
03/05-02-086-07-W4/0	269	AMOCO AOSTRA H-3 GLISP EX 5-2
AA/06-13-087-07-W4/0	185	COSEKA 1 TOT LYNTON OV 6-13
AA/09-31-087-08-W4/0	192	CDN LANDMASTERS GREGOIRE 9-31
AA/10-11-087-16-W4/0	267.5	PEX PCEJ MCMURRAY OV 10-11
AA/10-03-088-06-W4/0	170	WLSC CLEARWATER 10-3
AA/04-08-089-07-W4/0	184.7	HUSKY 23 MCMURRAY OV 4-8
AA/16-19-089-07-W4/0	180.7	HUSKY 24 MCMURRAY OV 16-19
AA/12-34-089-08-W4/0	203	MOBIL CLARKE OV 12-34
AA/07-14-089-09-W4/0	126.2	HUSKY 4 MCMURRAY OV 7-14
AA/12-14-089-10-W4/0	189.8	ESSO BSL 40-41 OSLO OV 12-14
AA/06-20-089-10-W4/0	166.1	ESSO BSL 40-1 OSLO OV 6-20
AA/11-07-090-07-W4/0	203.5	MOBIL 90 CLARKE CREEK OV 11-7
AB/10-21-090-07-W4/0	195	MOBIL 90 CLARKE CREEK OV 10-21
AA/12-09-090-08-W4/0	187	MOBIL CLARKE OV 12-9
AA/01-23-090-10-W4/0	116.3	ESSO BSL OSLO 4-83 OV 1-23
AA/04-01-091-08-W4/0	192	MOBIL CLARKE OV 4-1
AA/03-20-091-08-W4/0	166.4	BAYSEL 10 STEEPBANK OV 3-20-91-8
AA/01-30-091-08-W4/0	166.4	BAYSEL 11 STEEPBANK OV 1-30-91-8
AA/16-26-091-09-W4/0	99.4	BAYSEL 20 STEEPBANK OV 16-26
AA/06-16-091-13-W4/0	175.8	PEX PCEJ MCMURRAY OV 6-16
AA/12-08-091-14-W4/0	209	PEX PCI MCMURRAY OV 12-8
AA/10-26-091-15-W4/0	217	PEX PCI MCMURRAY OV 10-26
AA/10-08-091-17-W4/0	246	RAX MCMURRAY OV 10-8-91-17
AA/16-23-092-08-W4/0	192	UNION MCM 2-75 OV 16-23
AA/03-01-092-09-W4/0	131.5	UNOCAL 89 MCMURRAY OV 3-1
AA/01-09-092-09-W4/0	134.4	CHEVRON 89 MCMURRAY OV 1-9
AA/12-15-092-09-W4/0	106.4	UNOCAL 89 MCMURRAY OV 12-15
AA/02-16-092-09-W4/0	104.6	SUNCOR L25 STEEPBANK 2-16
AA/05-30-092-09-W4/0	39.7	SUNCOR FLI STEEPBANK 5-30
AA/05-33-092-09-W4/0	120.4	SOBC 1-3 FEE LOT OV 5-33
AA/08-03-092-10-W4/0	64.9	SUNCOR L23 OV RUTH 8-3
AB/10-34-092-10-W4/0	73	OVPEX ET AL MCMURRAY #1

FACIES WELLS

AA/01-12-092-12-W4/0	136	SYN ATHA 60-07-1-9 OV 1-12
AA/04-17-092-12-W4/0	138.3	PEX PCEJ MCMURRAY OV 4-17
AA/01-24-092-12-W4/0	120.7	SYNCRUDE 24-92-12 OV 1-24
AA/15-26-092-12-W4/0	108	SYN ATHA 60-28-0-0 OV 15-26
AA/09-20-092-13-W4/0	193.3	AOSTRA UTF DOVER A072 OV 9-20
AA/10-23-092-13-W4/0	179.5	AOSTRA DOVER UTF A073 OV 10-23
AA/10-26-092-16-W4/0	225.9	PEX PCI MCMURRAY OV 10-26
AA/10-18-093-06-W4/0	266.5	SUNCOR 8 MUSKEG OV 10-18
AA/10-12-093-07-W4/0	267.3	STEEPBANK 1-75 OV 10-12
AA/04-14-093-07-W4/0	235	STEEPBANK 1-75 OV 4-14
AA/11-18-093-07-W4/0	226.8	STEEPBANK 2-75 OV 11-18
AA/02-21-093-07-W4/0	253.6	STEEPBANK 2-75 OV 2-21
AA/10-24-093-07-W4/0	262.7	STEEPBANK 2-75 OV 10-24
AA/12-36-093-07-W4/0	256.3	STEEPBANK 2-75 OV 12-36
AA/04-28-093-09-W4/0	138.1	ESSO 7-82 OSLO OV 4-28
AB/06-09-093-10-W4/0	200.1	SYNCRUDE 5-26-9-1 OV 6-9
AA/01-20-093-10-W4/0	58.5	SYN ATHA #6-34-6-8 OV 1-20
AB/16-03-093-11-W4/0	79	SYN ATHA #302949 OV 16-3
AA/06-06-093-11-W4/0	89	SYN ATHA 49-33-0-0 OV 6-6
AA/01-22-093-11-W4/0	125.1	SYN ATHA#27-42-0-0 OV 1-22
AA/01-32-093-11-W4/0	107.8	SYN ATHA #34-55-0-0 OV 1-32
AA/01-33-093-11-W4/0	110.4	SYNCRUDE 27-53-9-9 OV 1-33
AA/07-29-093-13-W4/0	108	AOSTRA UTF DOVER A077 OV 6-29
AA/10-08-093-17-W4/0	263	RAX MCMURRAY OV 10-8-93-17
AA/11-07-094-06-W4/0	290	CDN LANDMASTERS STEEPBANK 11-7
AA/09-19-094-06-W4/0	294	CDN LANDMASTERS STEEPBANK 9-19
AA/10-27-094-07-W4/0	289.1	CHEVRON STEEPBANK OV 10-27
AA/03-30-094-07-W4/0	203	CHEVRON STEEPBANK OV 3-30
AA/08-29-094-08-W4/0	114	ESSO 1-86 OSLO BSL 31 OV 8-29
AA/12-16-094-09-W4/0	66.5	HOME CH-23 ATHA OV 12-16
AA/09-11-094-10-W4/0	50.6	GULF 24 HARTLEYOV 9-11
AA/14-15-094-10-W4/0	38.7	HESS TEST HOLE #2
AA/07-26-094-10-W4/0	69.2	GULF 9 HARTLEY OV 7-26
AA/03-33-094-10-W4/0	35.7	GULF 1 HARTLEY OV 3-33
AA/01-07-094-12-W4/0	108.2	SYNCRUDE MILDRED OV 1-7
AA/02-12-094-12-W4/0	105.8	SYN ATHA #42-69-0-0 OV 2-12
AA/10-08-094-14-W4/0	201.5	PEX ELLS OV 10-8
AA/16-30-094-15-W4/0	269.8	SHELL 2 WEST ATHA OV 16-30
AA/10-11-094-16-W4/0	261.5	PEX PCI MCMURRAY OV 10-11
AA/05-26-095-01-W4/0	159.7	SHELL 8 ATHAE OV 5-26
AA/05-11-095-07-W4/0	248	CDCOG 17 MUSKEGR OV 5-11
AA/04-03-095-08-W4/0	142.6	ESSO 5-82 OSLO OV 4-3
AA/16-07-095-08-W4/0	128	ESSO 4-86 OSLO BSL 31 OV 16-7
AA/13-08-095-08-W4/0	125	ESSO 4-86 OSLO BSL 31 OV 13-8
AA/07-10-095-09-W4/0	119.7	ESSO 90-12 OSLO OV 7-10
AA/15-31-095-10-W4/0	87.7	SHELL ALS 5044 MUSKEG OV 15-31

FACIES WELLS

AA/12-26-095-11-W4/0	94.2	SUPTST 2-72-1C ATHA OV 12-26
AA/16-30-095-11-W4/0	93.6	BPSUPTST 72-6C ATHA OV 16-30
AA/04-20-095-12-W4/0	128	SUPTST 6C ATHA OV 4-20
AA/01-22-095-12-W4/0	86.9	SUPTST 2-73-1C ATHA OV 1-22
AA/01-23-095-12-W4/0	90.2	SUPTST 2-73-2C ATHA OV 1-23
AA/01-21-095-12-W4/0	91.1	SUPTST 1-73-12C ATHA OV 1-21
AA/09-24-095-12-W4/0	88.7	SUPTST 4C ATHA OV 9-24
AA/01-27-095-12-W4/0	102.1	SUPTST 2-73-3C ATHA OV 1-27
AA/01-01-096-07-W4/0	206	CDCOG 44 MUSKEGR OV 1-1
AA/16-07-096-08-W4/0	93.9	HESS 81-161 MCLAND OV 16-7-96-8
AA/09-12-096-08-W4/0	136.6	MOBIL 8 MUSKEGR OV 9-12
AA/04-07-096-09-W4/0	119.8	ALSANDS 18 HANGST OV 4-7
AA/03-02-096-10-W4/0	143.9	ALSANDS 27 HANGST OV 3-2
AA/14-30-096-10-W4/0	145.3	CAN-AMERA STEEP OV 1-84 14-30
AA/09-02-096-12-W4/0	130.8	SUPTST 1-73-2C ATHA OV 9-2
AA/09-03-096-12-W4/0	141.4	SUPTST 3C ATHA OV 9-3
AA/06-08-096-14-W4/0	320	TEXACO NAMUR 3-81 OV 6-8
AA/03-02-096-15-W4/0	331	TEXACO NAMUR 3-81 OV 3-2
AA/08-18-096-16-W4/0	401.2	TEXACO NAMUR 3-81 OV 8-18
AA/03-28-096-16-W4/0	416.5	TEXACO NAMUR 3-81 OV 3-28
AA/04-08-098-12-W4/0	275	AQUIT ET AL ATHA OV 4-8
AA/16-21-098-13-W4/0	567.3	AQUIT ET AL ATHA OV 16-21
AA/11-26-099-15-W4/0	487.5	TEXACO NAMUR 2-81 OV 11-26
AA/06-31-101-12-W4/0	571	TEXACO NAMUR 1-81 OV 6-31
AA/13-31-103-12-W4/0	117.3	UNION MCIVOR #6 OV 13-31

Appendix 4. Palynological Study of Selected Core Examined in the Present Study

PALYNOLOGICAL ANALYSIS OF THE STEEPBANK 1-29-92-9W4 & 10-29-92-9W4 WELLS, NORTHEASTERN ALBERTA

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Project 98.28
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SECTION 1 INTRODUCTION

Twenty one samples from the 10-29-92-9W4, ten from the 1-29-92-9W4 and one outcrop sample were prepared for palynological analysis. The objective of the study was to establish the palynological sequence in the pre-McMurray and McMurray formations and the Wabiscaw Member of the Clearwater Formation in 10-29, and correlate the pre-McMurray to lower Middle McMurray section in the 1-29 well with the longer section.

Recoveries in the 10-29 well were often excellent but those in 1-29 were much poorer. The proportions of various palynomorph groups were determined to help interpret the environments of deposition and these data are presented on four charts (pages 14, 15, 17 and 18). The semiquantitative distributions of individual species are plotted on charts at a scale of 1:500 in an appendix.

The succession of first stratigraphic appearances of spores and pollen in 10-29 suggests that a zonation scheme for local zonation of the Middle and Upper McMurray is feasible. Confirmation of this will have to wait until other sections are studied since the recoveries are poor in 1-29 and that core does not contain the entire McMurray sequence. In spite of the poor data in 1-29, a correlation line is tentatively suggested between the 213.28' sample in that well and the 69m level in 10-29.

For the present study, the published stratigraphic ranges of key palynomorph taxa were reassessed and only the most reliable records were used.

SECTION 2 PREVIOUS RESEARCH

Burden (1984) published a spore-pollen zonation and age interpretation for the lower part of the Mannville Group. This was based in part on McMurray Formation sections including the outcrop on the Steepbank River located in the south-east quarter of 15-30-92-9W4.

In the Steepbank section, he described a spore assemblage in the Lower McMurray (CI Zone) which contained Neocomian spores and he assigned this a late Valangian or Hauterivian age.

He implied that the overlying TA assemblage is conformable but admitted that there was an unstudied interval between the two zones. The TA Zone was assigned an Early Barremian age which conflicts with his records of dinocysts which do not appear in stratigraphic record until the Aptian. The TA Zone was not delimited in the Steepbank section. The upper part of the Middle McMurray and the Upper McMurray were assigned to the CP Zone and given a Late Barremian to Late Aptian/earliest Albian age.

The dinocysts he recorded in the Lower McMurray clearly indicate that the Middle McMurray is not older than Aptian and the remaining age assignments need to be re-assessed.

In the present study, no early Neocomian species were recorded. In addition to this, the pre-McMurray sediments in both wells contained a dinocyst which does not range below the Middle Barremian. However, no species were recorded which become extinct in the Barremian. Dr. W .W. Brideaux, in his submission to the AEUB Hearing between Hillcrest Resources et al. and Truax Resources et al. (April 1995) stated that there is no evidence for an age older than Aptian for the base of the Mannville.

It is possible that there are isolated pockets of Necomian sediments below the Mannville but in a recent extensive study of Basal Quartz channels, no early Neocomian markers were recorded.

The palynological succession can be divided into four parts:

Interval	Formation	Age
16m - 25m	Wabiskaw Mbr.	Early Albian
25m - 71.5m	Upper to Middle McMurray	Aptian
71.5m - 83m	Lower McMurray	Probably Aptian
83m - 85.6m	Pre-McMurray	Probably Aptian (-?Middle Barremian)

Interval: **83m - 85.6m**
Samples: 83.5m, 85.6m
Formation: Pre-McMurray
Age: Probably Aptian (-?Middle Barremian}

Remarks

These two samples come from pre-McMurray strata and represent karst surface infilling by a Cretaceous marine incursion. They contain a small number of dinocysts including *Palaeoperidinium cretaceum*. This distinctive species usually makes its first appearance in the Late Barremian but has been recorded in the Middle Barremian of England. Also present are specimens of *Circulodinium* cf. *distinctum*, *Tanyosphaeridium variecalamum*, *Oligosphaeridium* spp., *Sentusidinium* spp. and *Canningia* spp., all of which have relatively long ranges. The terrestrial fraction consists of long-ranging pollen and spores but bisaccate pollen dominate. Rare specimens of *Lecaniella foveata (Zygnemataceae)* are also present. The lower range of this species is not known but it appears to have an Aptian - Cenomanian range.

Although a Barremian age cannot be ruled out, an Aptian age is more likely and an Aptian (-?Middle Barremian) age is tentatively assigned.

Interval: **71.5m - 83m**
Samples: 73.3m, 73.85m, 79.75m, 81.7m
Formation: Lower McMurray
Age: Probably Aptian

Remarks

The lowest sample (81.7m) is dominated by reworked Devonian acritarchs, scolecodonts and spores which together comprise over 96% of the assemblage. The other samples contain a long-ranging spore-pollen association similar to those in the pre-McMurray. Dinocysts are rare and have little or no stratigraphic value. None of the Neocomian spores recorded by Burden (1984) in the Lower McMurray in the Steepbank outcrop were present.

An Aptian age is tentatively assigned.

Interval: **25m - 71.5m**
Samples: 27.75m, 30m, 34.75m, 42.3m, 46.15m, 52.15m, 53.5m, 59m, 61.88m, 69m
Formation: Middle to Upper McMurray
Age: Aptian

Remarks

There is a major increase in richness and diversity in the spore-pollen assemblage at the base of the Middle McMurray. Bisaccate pollen continue to dominate but the spore fraction is much more diverse than in the underlying intervals. Important species which appear in the basal sample include:

Appendicisporites bilateralis
Cicatricosisporites augustus
Concavissimisporites tribotrys
Couperisporites tabulatus
Dictyotriletes granulatus
Foraminisporis asymmetricus
Microreticulatisporites uniformis
Triporoletes simplex

These are considered to be Aptian and younger species and *M. uniformis* probably first appears in the Early but not earliest Aptian. In the overlying samples, other species appear which are considered to appear in the Aptian including:

Crybelosporites brenneri
Parvisaccites rugulatus
Ischyosporites areolatus
Podosporites granulatus

Angiosperm pollen are extremely rare and the important species *Clavatipollenites minutus* is present at 53.5m. This is an index form for the CP Zone (mid to upper Middle McMurray) of Burden (1984).

Dinocysts are also extremely rare and consist of thin, hyaline forms typical of fresh to slightly brackish environments.

The presence of *Concavissimisporites* cf. *informis* at 30m implies that the section is still Aptian at this level. No samples were processed from the Upper McMurray.

Interval: **16m - 25m**
Samples: 18.4m, 19.95m, 21.55m, 24.48m
Formation: Wabiscaw Member of the Clearwater Formation
Age: Early Albian

Remarks

These samples yielded abundant dinocysts with a concomitant drop in the richness and diversity of the terrestrial fraction. The assemblages are dominated by specimens of *Palaeoperidinium cretaceum*, *Canninginopsis colliveri* and *Oligosphaeridium* spp. and the diversity of the microplankton assemblages increases upsection.

The age is based on the presence of *Odontochitina costata, Leptodinium cancellatum* and *L. delicatum,* which first appear in the Albian, and the essentially Albian and younger forms *Ellipsoidictyum imperfectum* and *Cyclonephelium paucispinum.*

L. cancellata and *L. delicata* were first described from Middle Albian rocks (Brideaux & McIntyre, 1975) and these occurrences extend their ranges downwards since there is ample macrofossil evidence for an Early Albian age for the Clearwater.

Recoveries from this well were generally much poorer than in the 10-29 core. Furthermore, the Lower McMurray is thicker here and only the lower part of the Middle McMurray is represented.

Interval	Formation	Age
213.28' - 266'	Middle McMurray	Aptian
266' - 290'	?Lower McMurray	Probably Aptian
290' - 340'	Lower McMurray	Probably Aptian
340' - 402'	Pre-McMurray	Probably Aptian (-?Middle Barremian)

Interval:	**340' - 402'**
Samples:	350.5', 383'
Formation:	Pre-McMurray
Age:	Probably Aptian (-?Barremian)

Remarks

The assemblages from these two samples are similar to those from the pre-McMurray in the 10-29 core. The upper sample contains *Palaeoperidinium cretaceum,* which does not range below the Middle Barremian, and the longer ranging forms *Batioladinium jaegeri* and *Oligosphaeridium complex* .

As in 10-29, although a Barremian age cannot be ruled out an Aptian age is more likely and an Aptian (- ?Middle Barremian) is tentatively assigned.

Interval: **290' - 340'**
Samples: 293.51', 338'
Formation: Lower McMurray
Age: Probably Aptian

Remarks

These two samples yielded extremely poor assemblages of long-ranging spores and pollen. There are insufficient data to interpret the age and the assignment is based on the underlying and overlying sections.

Interval: **266' - 290'**
Samples: 267.08', 268.45', 287.8'
Formation: ?Lower McMurray
Age: Probably Aptian

Remarks

These assemblages are richer and more diverse than those in the Lower and Pre-McMurray but are comparable with the Lower and Pre-McMurray in 10-29. *Pristinuspollenites sulcatus,* present at 268.45' probably first appears in the Aptian.

Interval: **213.28' - 266'**
Samples: 213.28',218.19',227.36'
Formation: Middle McMurray
Age: Aptian

Remarks

There is a slight increase in diversity here but the samples are poor when compared with those from the equivalent part of the 10-29 core.

The appearance of *Microreticulatisporites uniformis* at 213.28' is significant. This species, which first appears in the Early but not earliest Aptian, occurs down to 6-9m in the 19-29 core. A correlation line could tentatively be drawn between these two points.

To determine the proportions of the palynomorph taxa, a count of 200 specimens was made where possible. In some poor samples there were less than 200 specimens on the entire slide and in 10-29 at 59m and 61.88m counts of 300 were made. The palynomorphs were assigned to biological groups to aid in the interpretation of the environments of deposition. The groups used are:

Group	Environment
Pteridophyte spores misc.	Swamp
Bisaccate pollen	Hinterland contribution
Taxodiaceae	Lowland floodplain swamps
Other gymnosperms	
Classopollis	Arid/semi-arid hinterland
Schizaceae	Stressed environment, flooding/drying cycles
Angiosperm pollen	
Algae (Freshwater)	
Botryoccocus	lacustrine
Zygnematacceous spores	
Algae (Marine)	
Dinocysts Ceratioid	Abundance of some forms indicates reduced salinity
Peridinioid	Abundance of some forms indicates reduced salinity
Chorate	More abundant in open marine
Proximate	
Simple (indet.)	Unassignable. Usually fragments.

The proportions and degree of sorting of the organic macerals was also determined where possible to help with the environmental interpretation. Unfortunately, many of the residues were unavoidably contaminated with an oily or waxy substance from the heavy oil in the core, which obscured the macerals.

The data are presented in both numeric and percentage abundance formats (pages 14, 15, 17 and 18). It is evident from the charts that recoveries were much better in 10-29. Samples in this well often yielded five times more palynomorphs than the best samples in 1-29.

10-29-92-9W4

Pre-McMurray

The assemblages from these karst infill deposits are dominated by bisaccate pollen with rare dinocysts which suggest a brackish, estuarine equivalent environment establish during a marine incursion.

Lower McMurray

The basal sample (81.7m) is overwhelmingly dominated by reworked Devonian taxa, but a fragment of *Oligosphaeridium pulcherrimum* indicates some marine influence. The recovery from 79.95m is small and dominated by bisaccate pollen. Rare ceratioid dinocysts similar to those in the Pre-McMurray indicate some faint marine influence. Bisaccates dominate the 73.85 sample but spores predominate at 73.3m where rare ceratioid cysts indicate a faint saline influence.

The overall impression is of a fluvial setting with occasional, weak, saline conditions.

Middle McMurray

The lower five samples (69m - 52.15m) are dominated by bisaccate pollen indicating a high hinterland contribution which is further emphasized at 61.88m and 53.5m by larger than usual numbers of the arid/semi-arid hinterland pollen *Classopollis*. Sorting is extremely poor which indicates low energy and the kerogens are dominated by sapropels and vitrinite. The 59m sample has rare hyaline dinocysts typical of freshwater deposits. Lacustrine/abandoned channel deposits might be expected to yield similar assemblages.

The yield at 46.15m is lower and the kerogen is dominated by coaly material and amorphous vitrinite typical of coal swamps. The three assemblages from 42.3m - 30m are similar to those in the lower part of the Middle McMurray. The swamp influence returns at 27.75m but the hinterland contribution is still high.

The palynological data suggest a fluvio-lacustrine environment for the Middle McMurray at this location. The formation is usually considered to have been deposited in a tidal, estuarine setting but in this study no evidence of marine influence was encountered. Samples in 1-29 also contain freshwater algae.

Wabiskaw

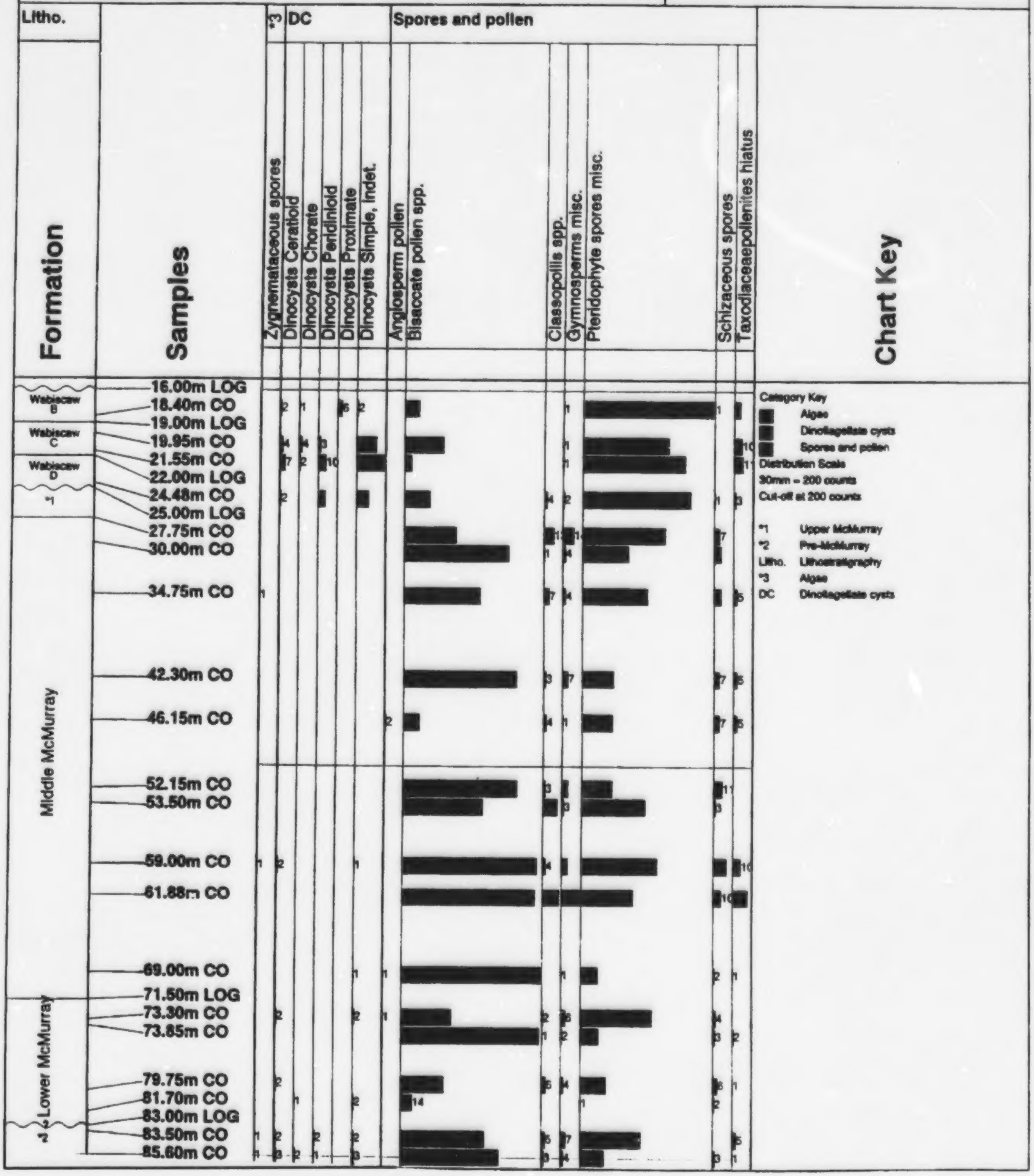
There is a marked change in these very rich assemblages. Spores become predominant and dinocysts are abundant. Reduced salinities are indicated in the lowermost sample (24.48m) where there are high numbers of peridinioid and ceratioid cysts. An increase in diversity of the dinocyst assemblages upsection points to the establishment of normal marine salinities. The relatively low pollen to spore ratio indicates that the swamp influence is high and a lower estuarine to nearshore marine setting is indicated.

Well Name: 10-29-92-9W4 FACIES

Operator:
Interval : 16.00m - 85.60m
Scale : 1:500
Date : 10-February-1999
PALYNOMORPH GROUPS

Style : Numeric Abundance Histogram
Author: G. Dolby

G. Dolby and Associates
Calgary, Alberta, Canada



1-29-92-9W4

Pre-McMurray

The lower sample yielded a non-marine assemblage with a high hinterland component. The kerogen is dominated by coaly debris. The upper assemblage at 350.5' is dominated by the hinterland component and also contains rare dinocysts which indicate a brackish, estuarine equivalent environment.

Lower McMurray

The yields here are too low to determine the environment with any confidence.

?Lower McMurray

The hinterland component (bisaccates and *Classopollis)* is high in all three samples. The kerogen from 287.8' is dominated by coaly material suggesting a strong swamp influence. The 268.45m residue is similar but also contains numerous *Botryococcus* colonies indicative of freshwater, possibly lacustrine conditions.

The 267.08' sample yielded few spores and pollen and the kerogen is not only dominated by inertinite/semi-fusinite, but there is a tendency towards bimodal sorting. This could represent a flood deposit.

Middle McMurray

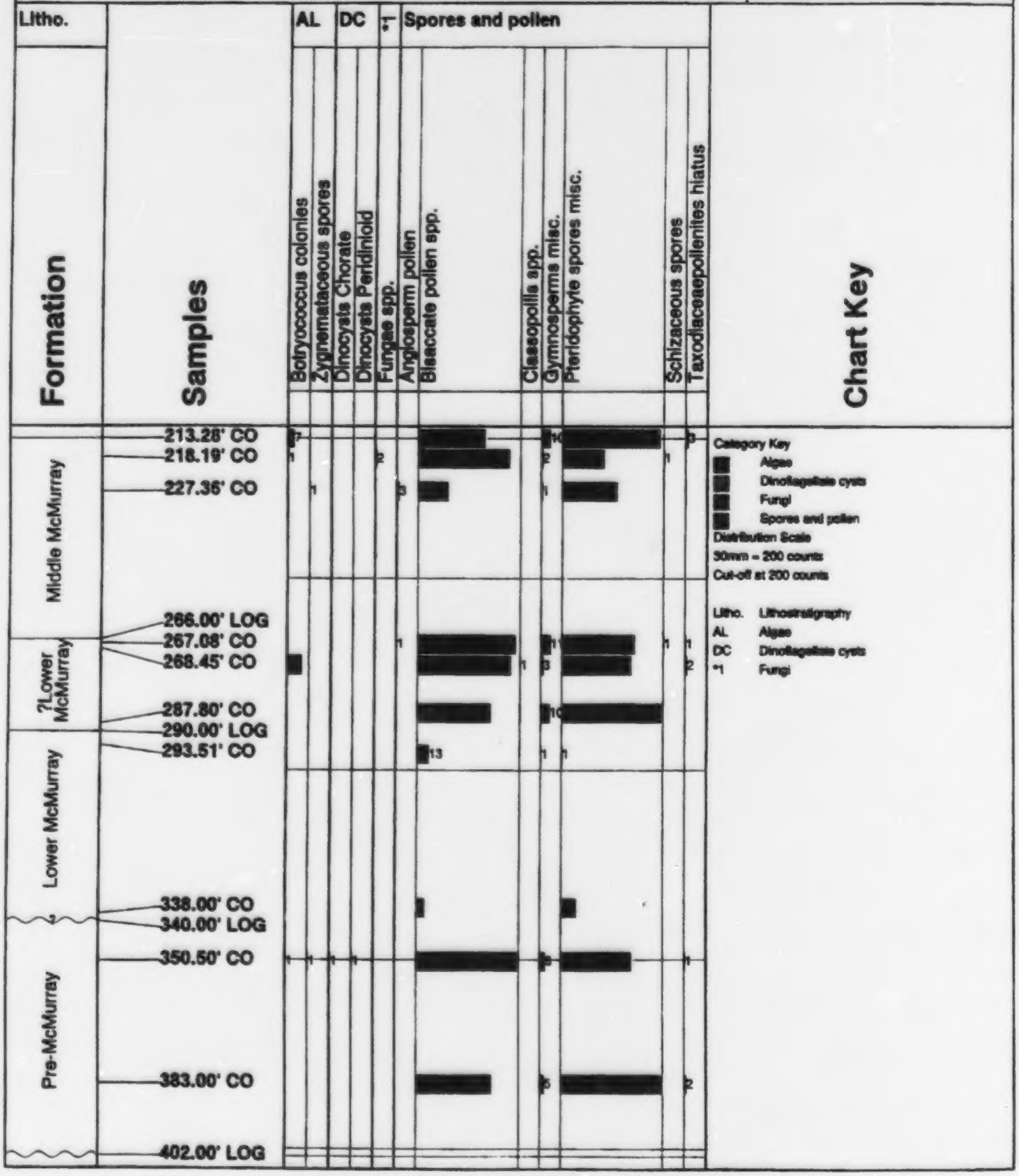
The kerogen in these samples, from near the top of the core, is dominated by coaly debris. In addition, *Botryococcus* colonies are prominent at 218.19' and 213.28'. This part of the section appears to represent freshwater, possibly lacustrine conditions.

Well Name: 1-29-92-9W4 FACIES

Operator:
Interval : 213.28' - 402.00'
Scale : 1:500
Date : 10-February-1999
PALYNOMORPH GROUPS

Style : Numeric Abundance Histogram
Author: G. Dolby

G. Dolby and Associates
Calgary, Alberta, Canada



SECTION 6 OUTCROP SAMPLE

A coaly fragment from an otherwise unpromising sandstone sample was processed and yielded a modest terrestrial assemblage of limited composition. Long-ranging bisaccate pollen predominate but specimens of *Lecaniella foveata* comprise 5% of the assemblage. The full range of this zygnemataceous spore is not known but it appears to be Aptian-Cenomanian.

Species recovered

Lecaniella foveata (A)

Cedripites canadensis *C. cretaceus*
Alisporites bilateralis *A. grandis*

Brideaux, W.W. & McIntyre, D.J. 1975. Miospores and microplankton from the Aptian - Albian rocks along the Horton River, District of Mackenzie. G.S.C. Bulletin 252.

Burden, E. T. 1984. Terrestrial palynomorph biostratigraphy of the lower part of the Mannville Group (Lower Cretaceous), Alberta and Montana.
C.S.P.G. Memoir 9, p.249-269.

The plotting program recognises the depths of core, sidewall core and cuttings samples as well as electric log depths. All depth information here is derived from cores. To distinguish between palynological samples and lithological boundary depths, sample depths are followed by the letters CO (core sample) and formation boundaries by LOG.

Appendix 5. Dominant Trace Fossils in the McMurray/Wabiskaw Interval

Bioturbation within the McMurray Formation is common throughout much of the succession. Select facies and facies assemblages within the McMurray succession often contain a definitive suite of trace fossils that are characteristic of particular facies. An overall bioturbation intensity pattern can be recognized throughout most of the Athabasca oil sands deposit. Burrowing intensity generally increases upwards within the succession reflecting the well documented transition from continental sediments (fluvial-dominated Lower McMurray) at the base to brackish water sediments at the top (estuarine-dominated Upper McMurray) (cf. Mattison and Pemberton, 1989; Mattison et al., 1989), that are unconformably overlain by marine sediments of the Wabiskaw Member. The McMurray Formation contains a low diversity trace fossil assemblage, with the burrowing intensities ranging from absent to burrow mottled (churned).

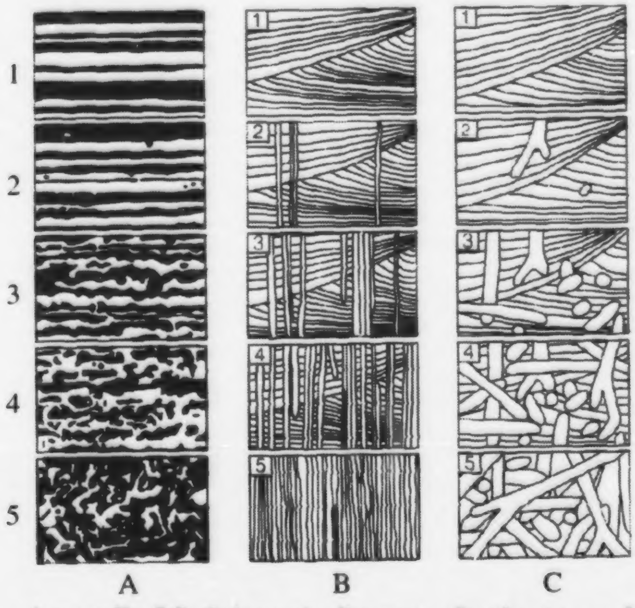
Burrowing within the fluvially dominated Lower McMurray succession ranges from absent to rare, generally limited to small *Planolites* generally found in light to medium grey, mud-dominated intervals. Estuarine sediments of the Upper McMurray display a large variation in bioturbation intensity (unbioturbated to completely bioturbated) with continued low diversity. Common traces include *Cylindrichnus*, *Planolites*, *Skolithos* and *Gyrolithes*. Less common traces include *Teichichnus*, *Asterosoma*, *Bergaueria*, and *Palaeophycus*. Rooting is somewhat common in both the Lower McMurray and the uppermost portion of the Upper McMurray. Traces within the McMurray succession tend to be much smaller in size compared to fully marine equivalent forms, some of which are found within the overlying Wabiskaw Member (cf. Ranger, 1992). This observation is particularly noticeable at the McMurray/Wabiskaw contact where traces in the Wabiskaw succession are markedly larger in size compared with the McMurray Formation equivalents. Trace fossils within the Wabiskaw Member commonly include large forms of *Thalassinoides*, *Asterosoma* and *Diplocraterion*. Less common traces include *Rhizocorallium*, *Rosselia*, *Monocraterion*, *Chondrites* and *Terebellina* (Wightman *et al.*, 1995).

Bioturbation is most prevalent within Facies 9B, 10, 12, 13, and 14 of the Upper McMurray Formation. These particular facies range from having thin mud interbeds to laminae within a sand-domainted succession to a fully mud-dominated succession. Rare burrowing in the Lower McMurray has been observed in Facies 3 and 4.

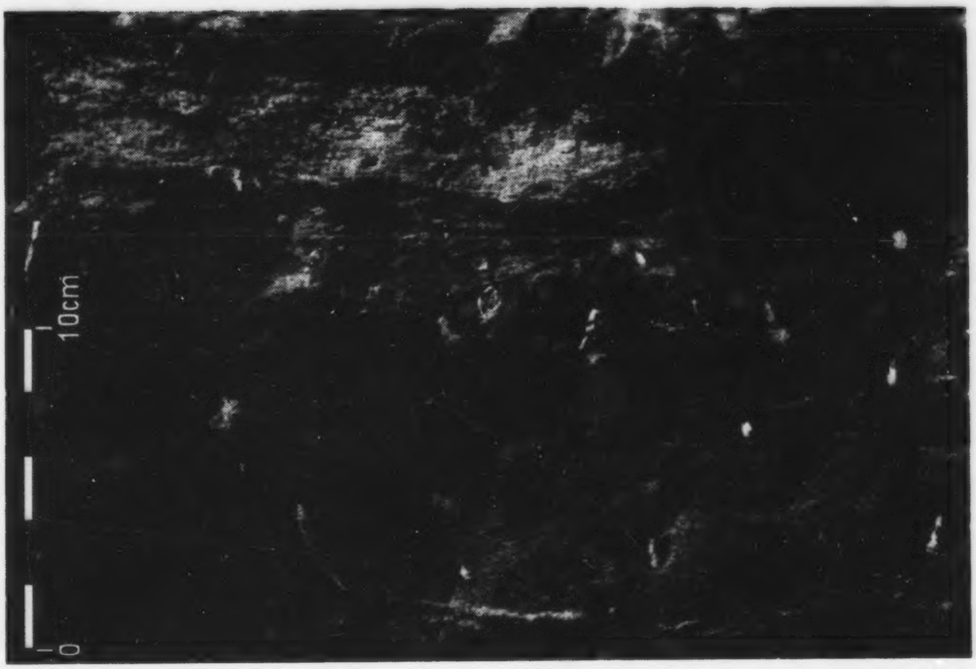
Table 5.1 and Appendix 5.0 (modified from Pemberton *et al.*, 1992a, b, c and Ranger and Pemberton, 1992) serves as a guide to the classification and degree of bioturbation discussed within the core and outcrop facies figures within this document. The most common trace fossils within the McMurray succession are shown in this appendix.

Grade	Percent Bioturbation	Classification
0	0	Unbioturbated
1	1-5	Very slightly bioturbated
2	5-30	Slightly bioturbated
3	30-60	Moderately bioturbated
4	60-90	Highly bioturbated
5	90-99	Intensely bioturbated (vestiges of some physical structures still discernable)
6	100	Completely bioturbated

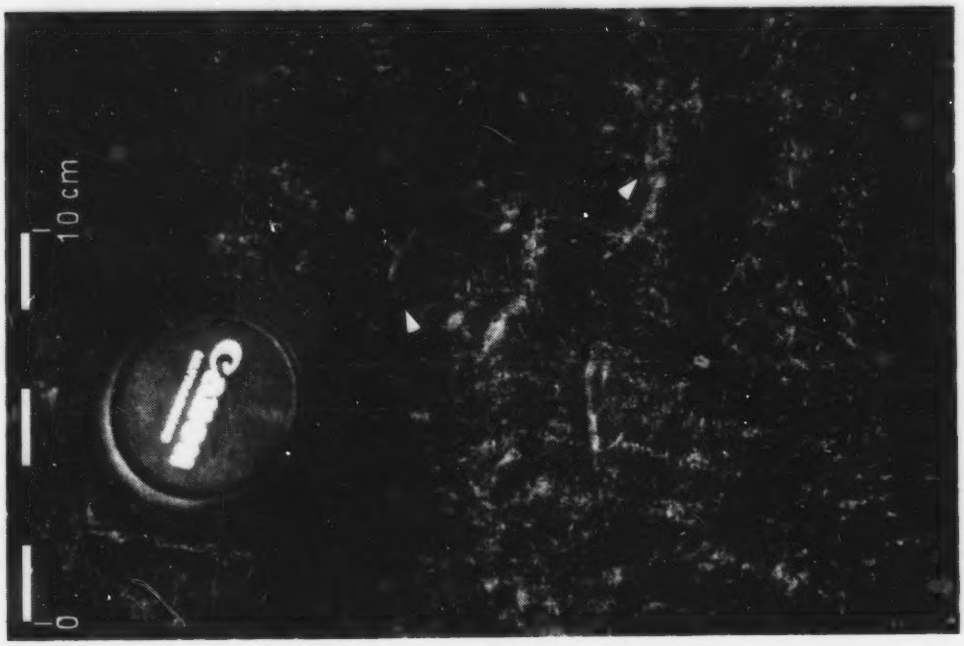
Table 5.1: Classification of bioturbation, based on destruction of primary sedimentary structures. *(Adapted from Reineck, 1967).*



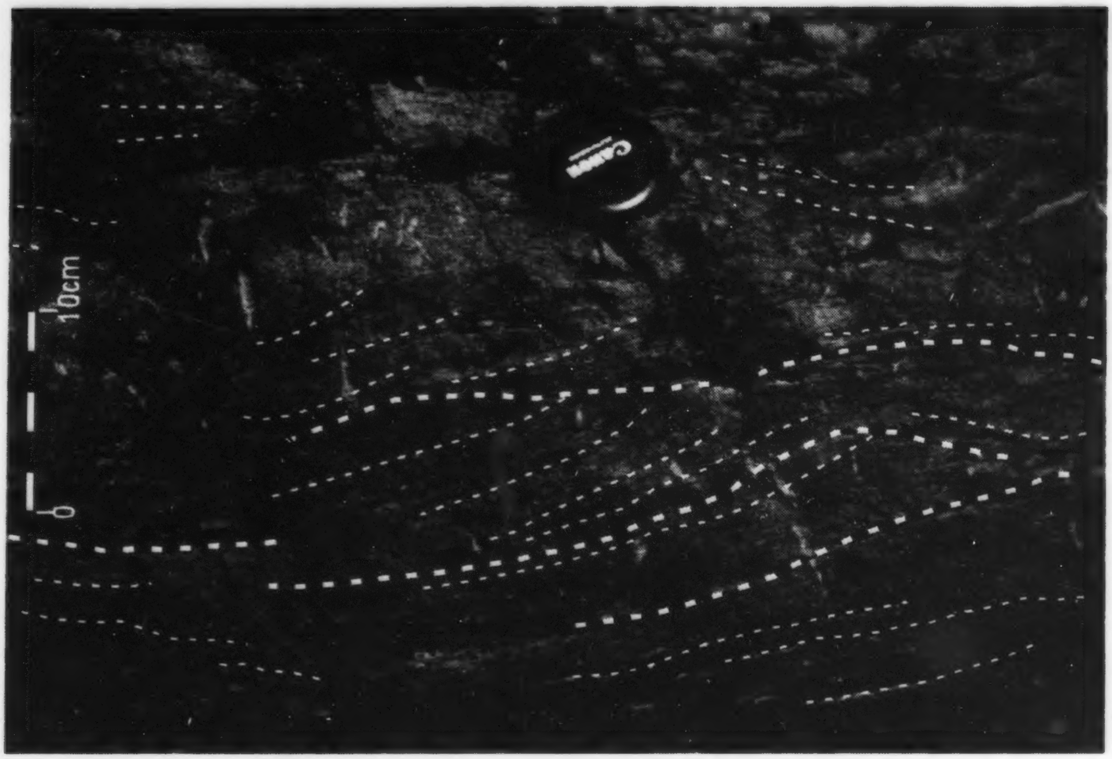
Appendix 5.0: Schematic diagrams of estimates on degree of bioturbation (ichnofabric index). (**A**) for thin bedded strata. (**B**) for thick bedded strata dominated by *Skolithos.* (**C**) for thick bedded strata dominated by *Ophiomorpha.* (*modified from S. George Pemberton et al. 1992*).



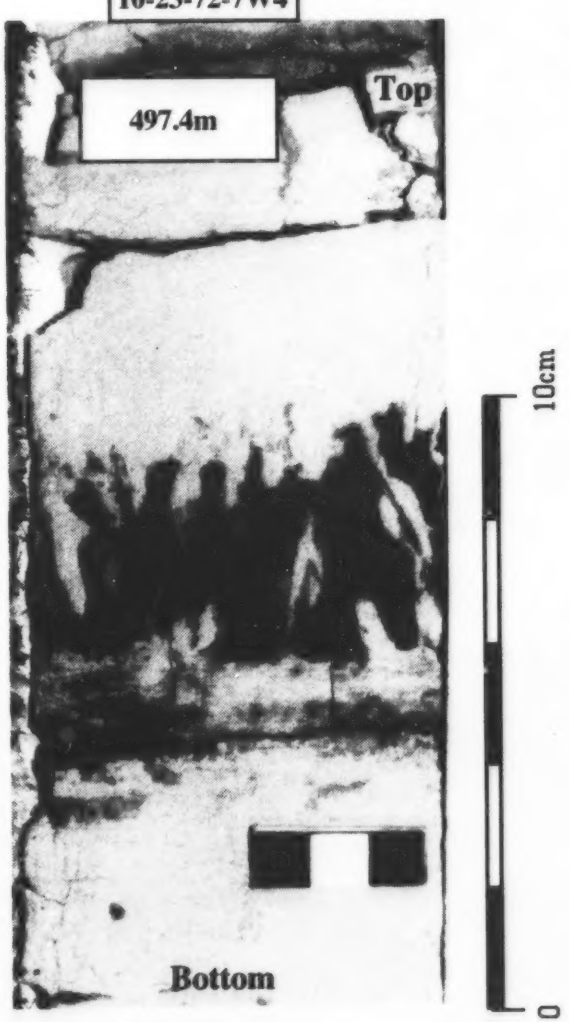
Appendix 5.1: *Cylindrichnus* burrows within rippled Upper McMurray Formation, Outcrop #3, Steepbank River. Facies 9A.



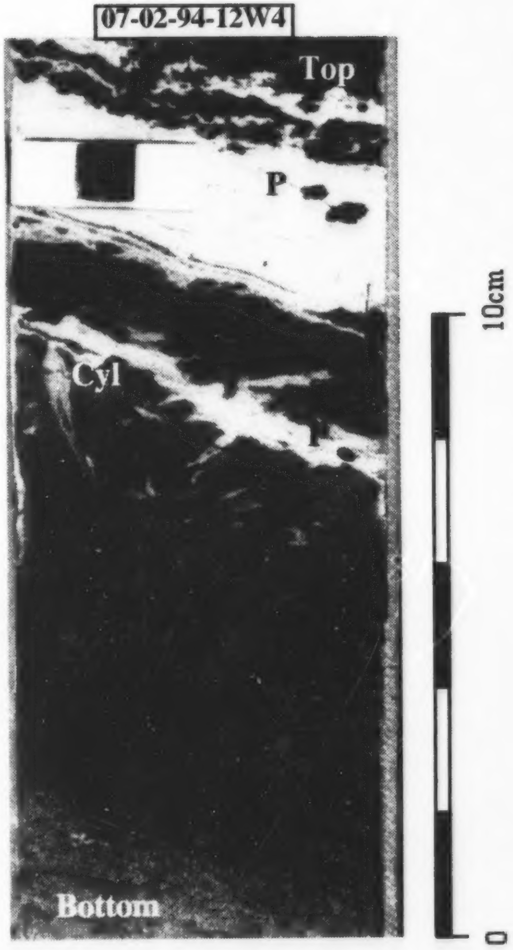
Appendix 5.2: Rare (in-place) *Cylindrichnus* (arrow) burrows found within trough cross-bedded McMurray sands, Saline Creek. Facies 5.



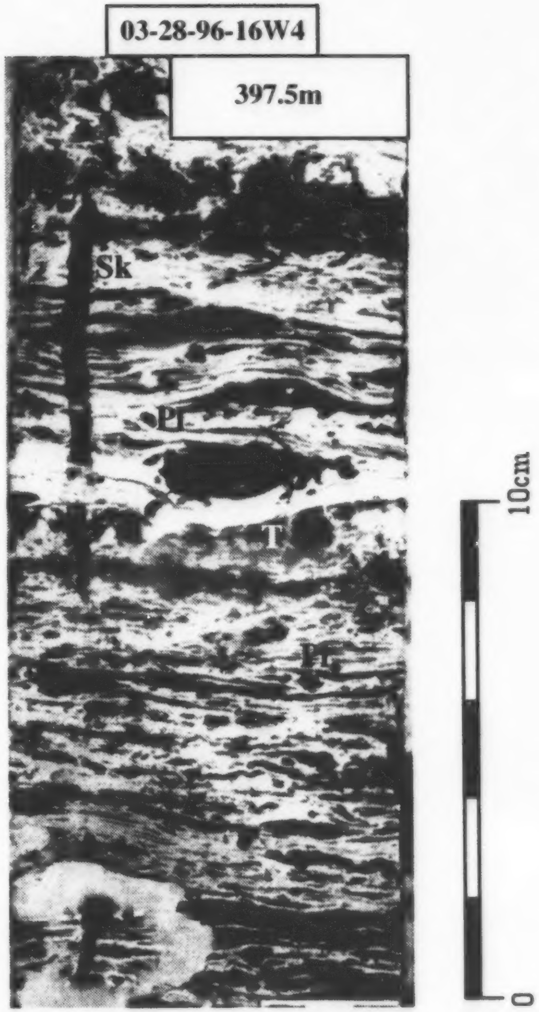
Appendix 5.3: *Cylindrichnus* burrows within small scale trough cross-bedded sand, Outcrop #3, Steepbank River. Rare occurrence of in-place burrows within trough cross-beds. Facies 5.


10-23-72-7W4
497.4m
Top
Bottom
10cm
0

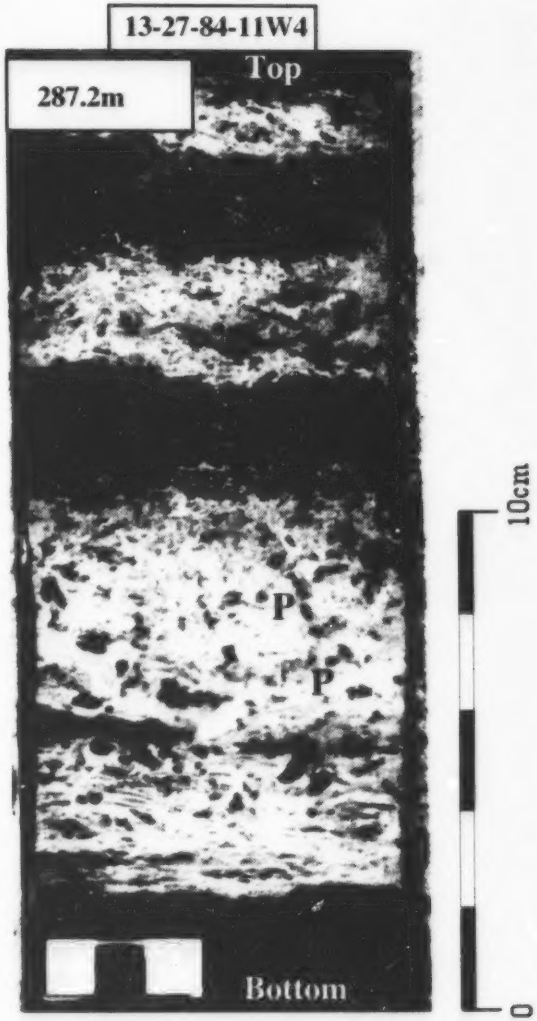
Appendix 5.4: *Cylindrichnus* burrows within mud-dominated, inclined heterolithic stratification. Facies 10B


07-02-94-12W4
Top
P
Cyl
Bottom
10cm
0

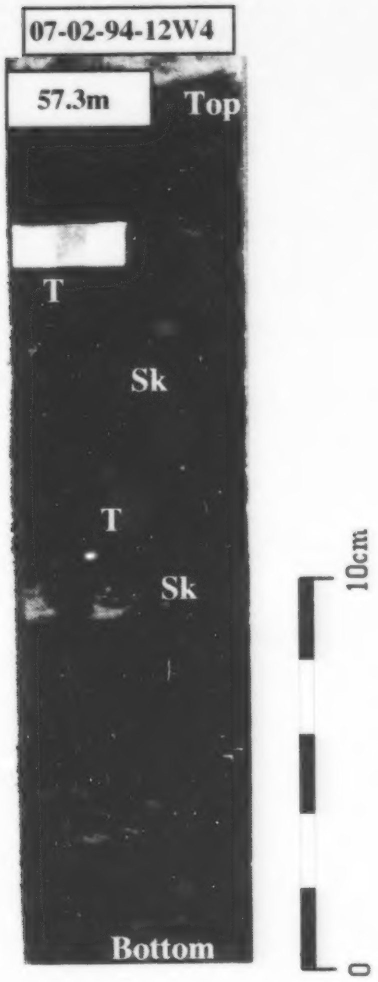
Appendix 5.5: *Cylindrichnus* (Cyl) and *Planolites* (P) burrows within sand-dominated, inclined heterolithic stratification. Facies 10A


03-28-96-16W4
397.5m
Sk
Pl
T
Pl
10cm
0

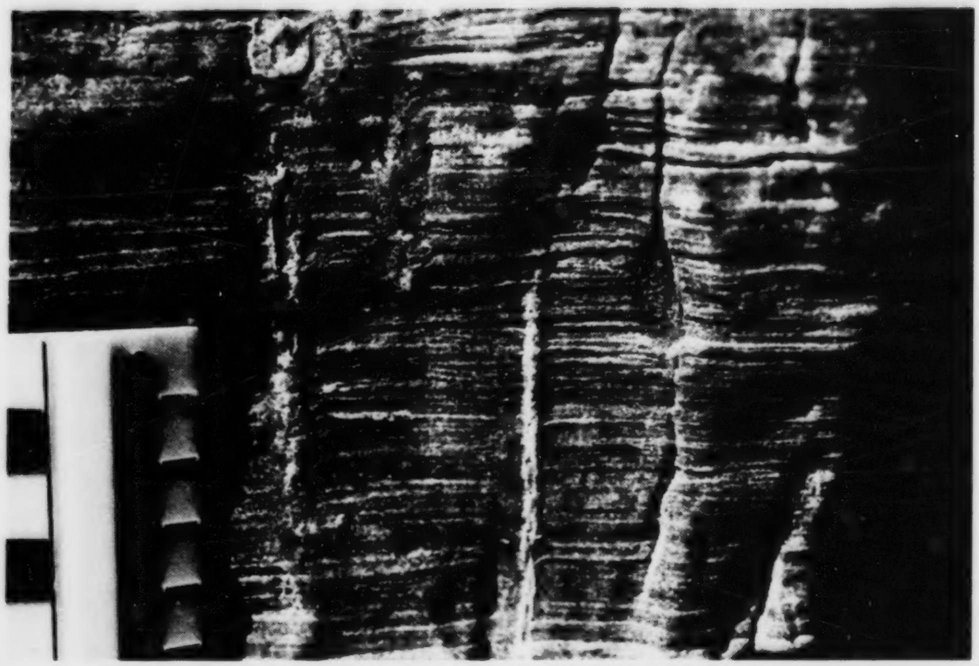
Appendix 5.6: *Skolithos* (Sk), *Planolites* (Pl) *and Teichichnus* (T) burrows. Facies 9B.


13-27-84-11W4
287.2m
Top
P
P
Bottom
10cm
0

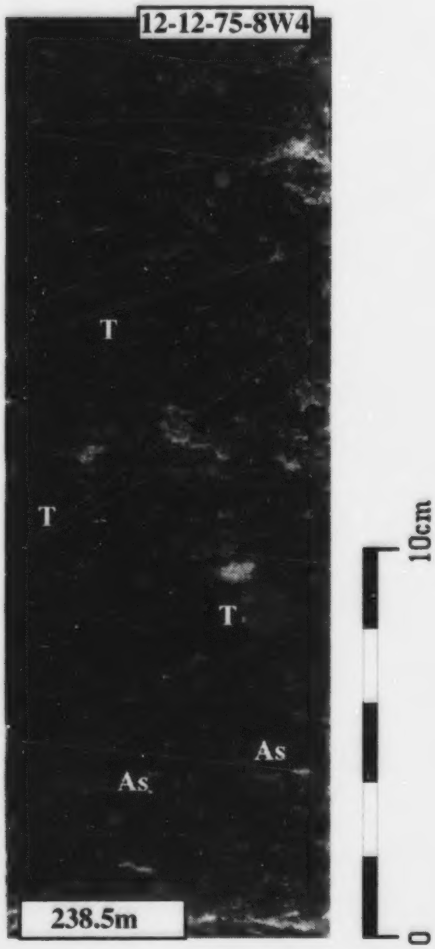
Appendix 5.7: *Planolites* (P) burrows within mud-dominated, inclined heterolithic stratification. Facies 10B.


07-02-94-12W4
57.3m
Top
T
Sk
T
Sk
Bottom
10cm
0

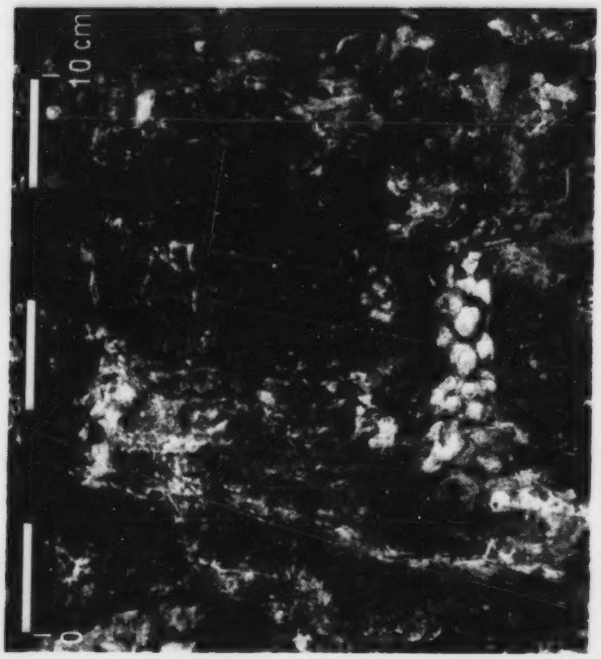
Appendix 5.8: *Skolithos* (Sk) and *Teichichnus* (T) burrowing. Facies 13A.



Appendix 5.9: Trace fossils *Skolithos* cross cutting parallel laminated sand, Upper McMurray Formation, View Point Section, MacKay River. Facies 11.


12-12-75-8W4
T
T
T
As
As
238.5m
10cm
0

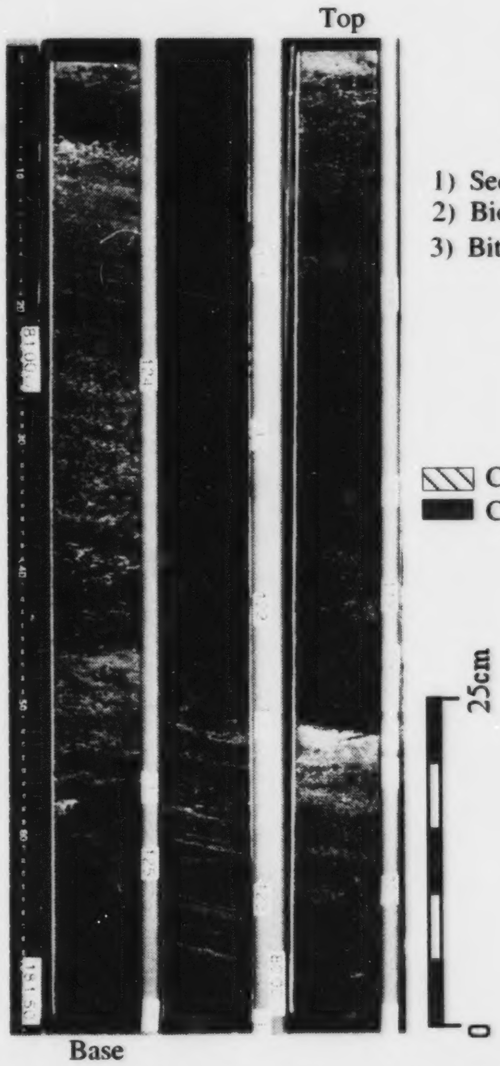
Appendix 5.10: *Teichichnus* (T) and *Asterosoma* (As). Facies 13A.



Appendix 5.11: *Gyrolithes* trace fossils in muddy sand, Upper McMurray Formation, View Point Section, MacKay River. Facies 12B.

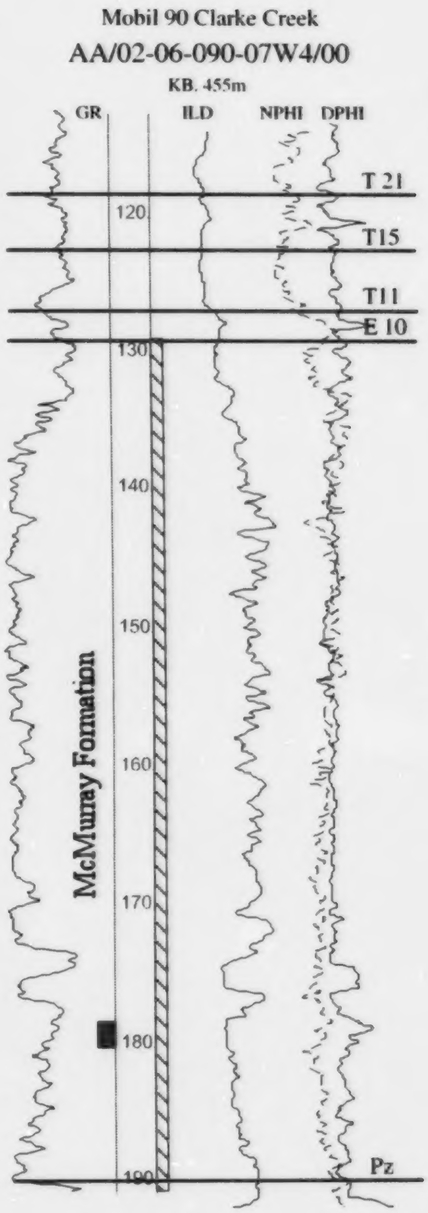
07-02-94-12W4
G
G
89.1m

Appendix 5.12: *Gyrolithes* (G) burrows within sand-dominated, inclined heterolithic stratification. Facies 10A.

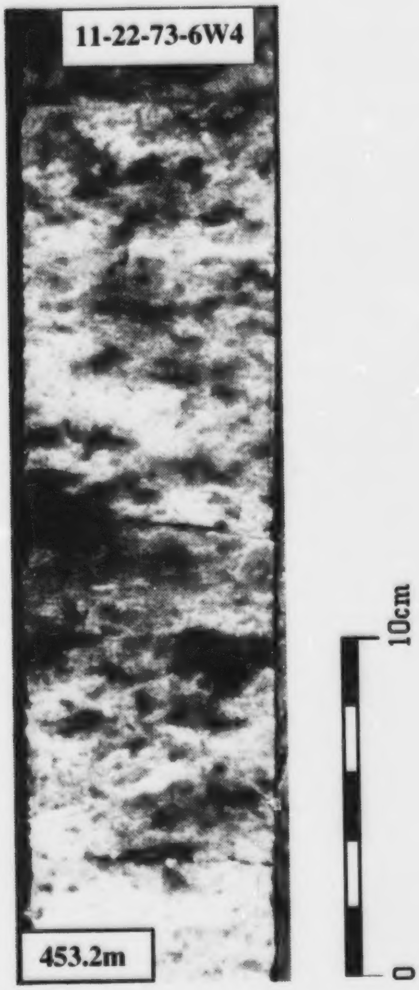


1) Sedimentary Features: burrow mottled and mud-flasers
2) Bioturbation Index: 4 to 5 (*Gyrolithes*)
3) Bitumen Saturation: fair to poor

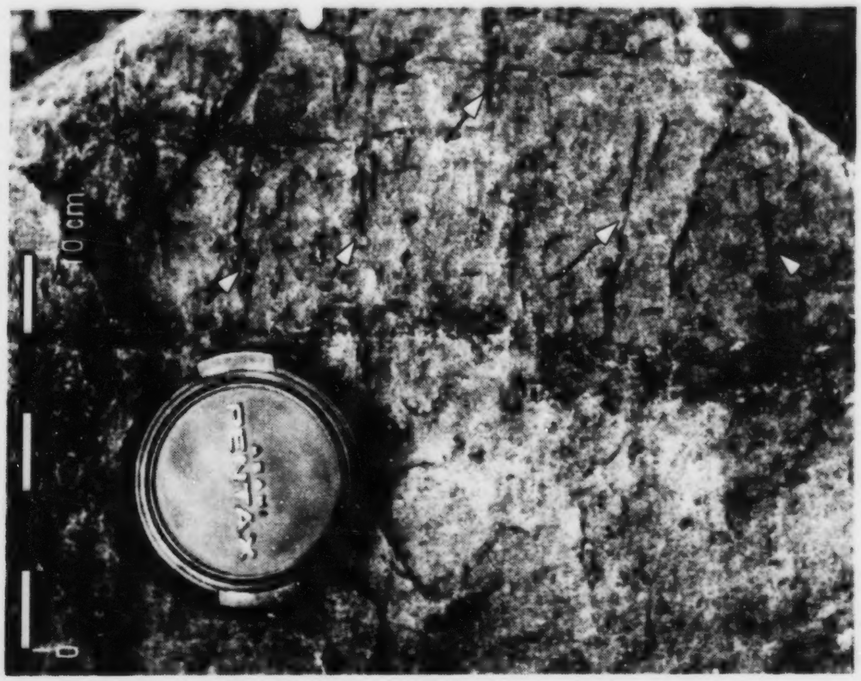
▨ Cored Interval
■ Core Interval Viewed



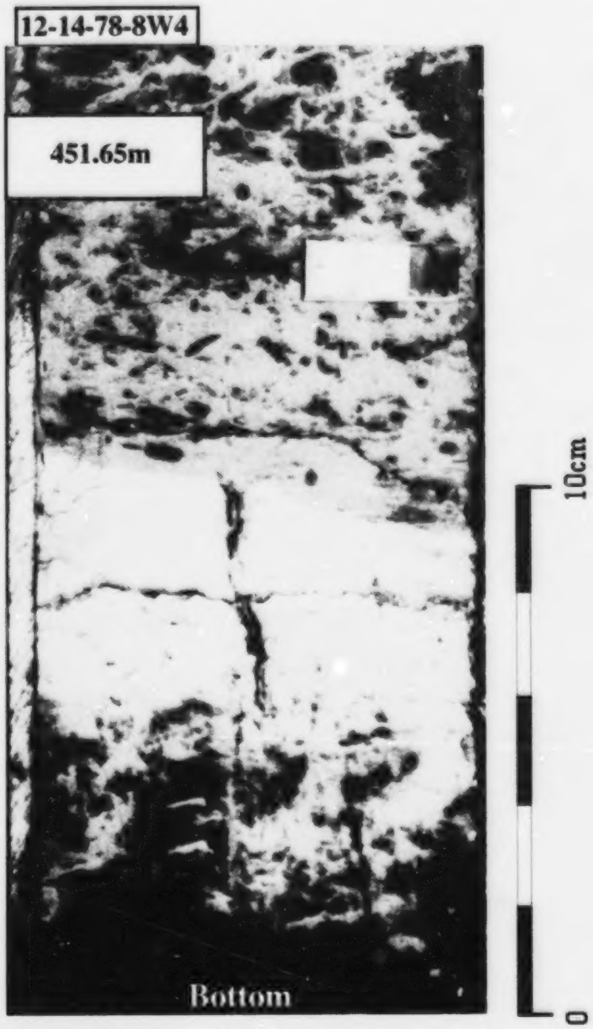
Appendix 5.13: Heavily burrowed *(Gyrolithes)* muddy sand to sandy mud. Geophysical log responses shown to the right.


11-22-73-6W4
453.2m
10cm
0

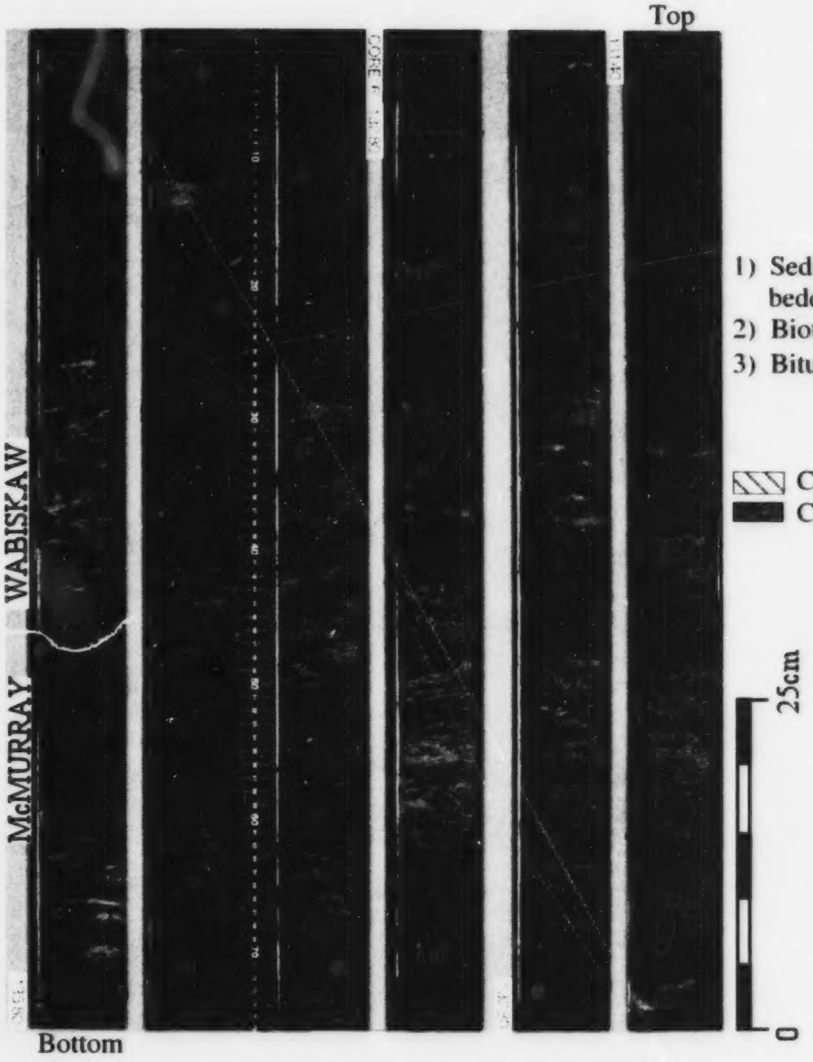
Appendix 5.14: Burrow mottled. Facies 13B.



Appendix 5.15: Rooted (arrows) siltstone from near the top of Outcrop #9-2, Steepbank River. Facies 14.

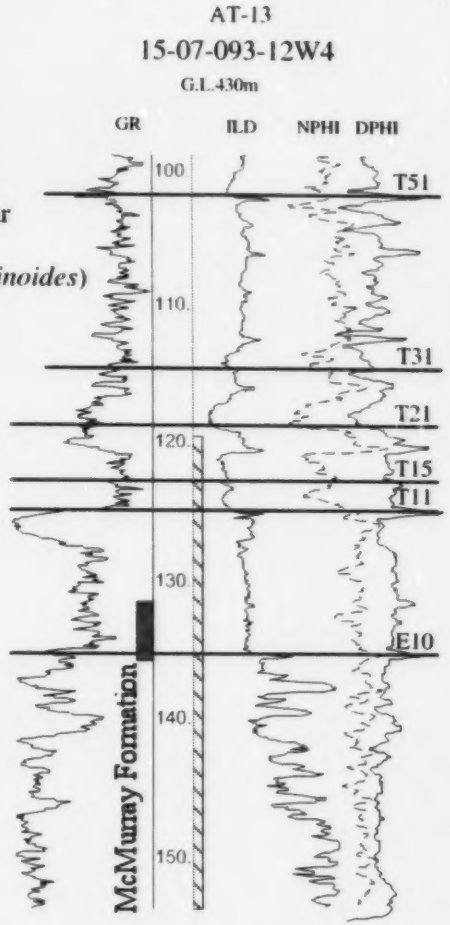

12-14-78-8W4
451.65m
Bottom
10cm
0

Appendix 5.16: Rooted horizon sharply overlain by Facies 13B

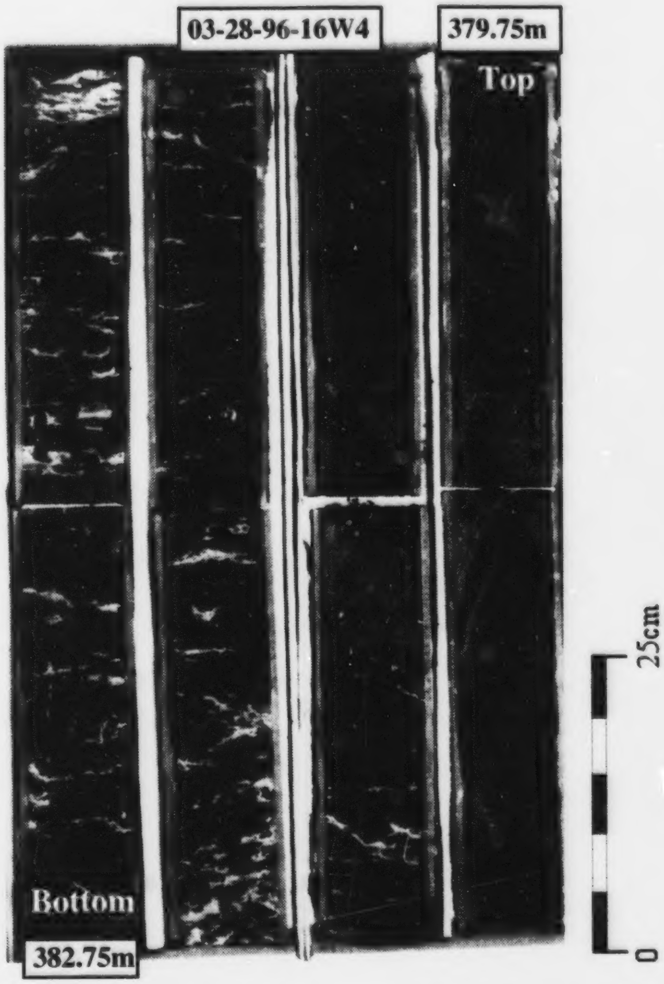

Top
Bottom
WABISKAW
McMURRAY
25cm
0

1) Sedimentary Features: lenticular bedding, mud flasers
2) Bioturbation Index: 3 (*Thalassinoides*)
3) Bitumen Saturation: poor

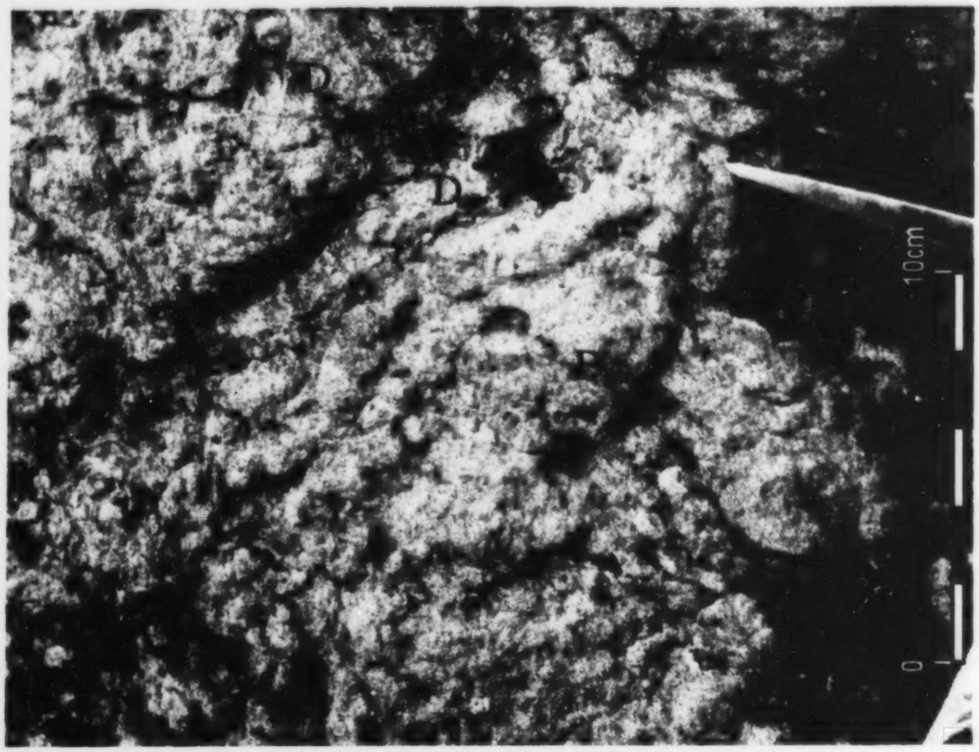
▨ Cored Interval
■ Core Interval Viewed



Appendix 5.17: Robust *Thalassinoides* within a mud-dominated portion of the Wabiskaw C-interval. Geophysical log responses shown to the right.


03-28-96-16W4
379.75m
Top
Bottom
382.75m
25cm
0

Appendix 5.18: *Thalassinoides* and *Asterosoma* burrows within the Wabiskaw D-interval.



Appendix 5.19: *Diplocraterion* (D) burrows within the Wabiskaw Member directly overlying the McMurray Formation, Outcrop #3, Steepbank River. Bedding plane top view. Facies 15.